ComPASS Beam Dynamics Overview

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for the ComPASS beam dynamics team

ComPASS DOE review
April 21, 2009

With contributions from

- Ji Qiang, C. Geddes, J.-L. Vay, X. Li, H. Shan (LBNL)
- J. Amundson, E. Stern, A. Macridin, P. Spentzouris (FNAL)
- D. Bruhwiler, P. Stoltz (Tech-X)
- W. Fischer, J. Kewisch (BNL)
- Y. Zhang, R. Li (JLab)
- A. Kabel (SLAC)

Codes developed or enhanced under ComPASS and applied to beam dynamics studies

- **IMPACT suite**
- **Synergia**
- **MaryLie/IMPACT**
- **VORPAL***

Broadly applicable frameworks

- **BeamBeam3D**
- **Nimzovitch**
- **Elegant**

Targeted apps

*primarily used for EM modeling, but also applied to beam dynamics studies of e-cloud effects and e-cooling physics

Applied to nearly all the major accelerator projects in HEP, NP, BES

Built upon frameworks and shared infrastructure and methodology:

- Optics: CHEF, PLIBB, MaryLie
- Modules for space-charge: Hockney, IGF, shifted IGF, spectral, Sphaerena, …
- Modules for: wakefields, e-cooling, e-cloud,…
- Algorithms: Boosted frames, particle pushers, Poisson solvers,…
- Parallelization approaches: domain decomp, hybrid decomp, p-scans
- Code performance, porting, infrastructure, verification and validation, I/O
- Data analysis and visualization

IMPACT code suite

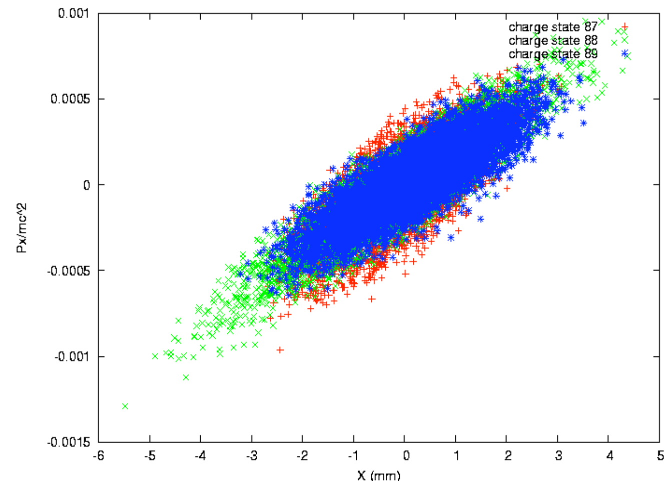
- **IMPACT-Z: parallel PIC code (z-code)**
- **IMPACT-T: parallel PIC code (t-code)**
- **Envelope code, pre- and post-processors**
- **Domain decomp, particle-field decomp**
- **Applied to HEP, NP, and BES projects**
  - CERN PS2
  - SNS, RIA, FRIB, ELIC, e-RHIC
  - Photoinjectors, future light sources, advanced streak cameras,…
  - 2009 INCITE project, Beam Delivery System Optimization for X-Ray FELs

# processors	time (sec)	mesh size	macroparticles (billions)	efficiency
1000	307.5	64x128x128	1.25	1.0
2000	308.7	64x128x256	2.5	0.996
4000	316.4	64x256x256	5	0.972
8000	320.8	64x256x512	10	0.958
16000	346.6	64x256x1024	20	0.887

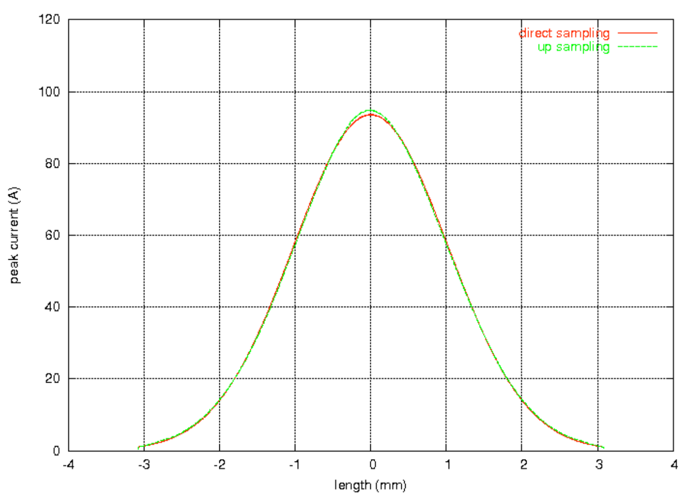
IMPACT-T weak scaling study on Franklin

IMPACT: Recent Enhancements

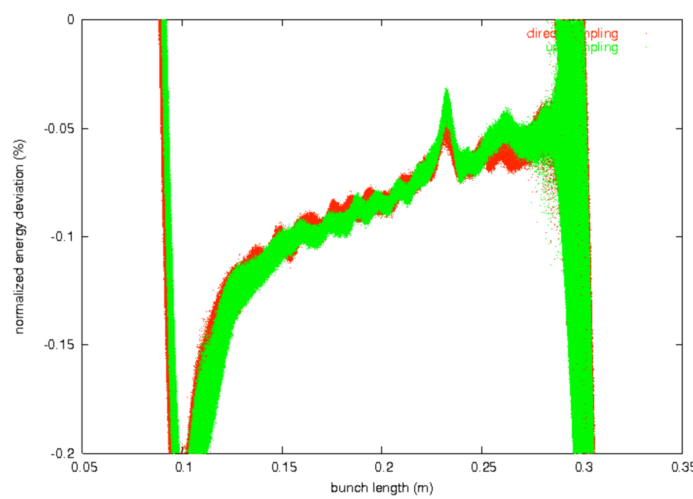
- Upsampling capability
- CSR
- Multi-charge state
- Improved Poisson solver
- Domain decomp/hybrid decomp performace study



RIA multi-charge state simulation

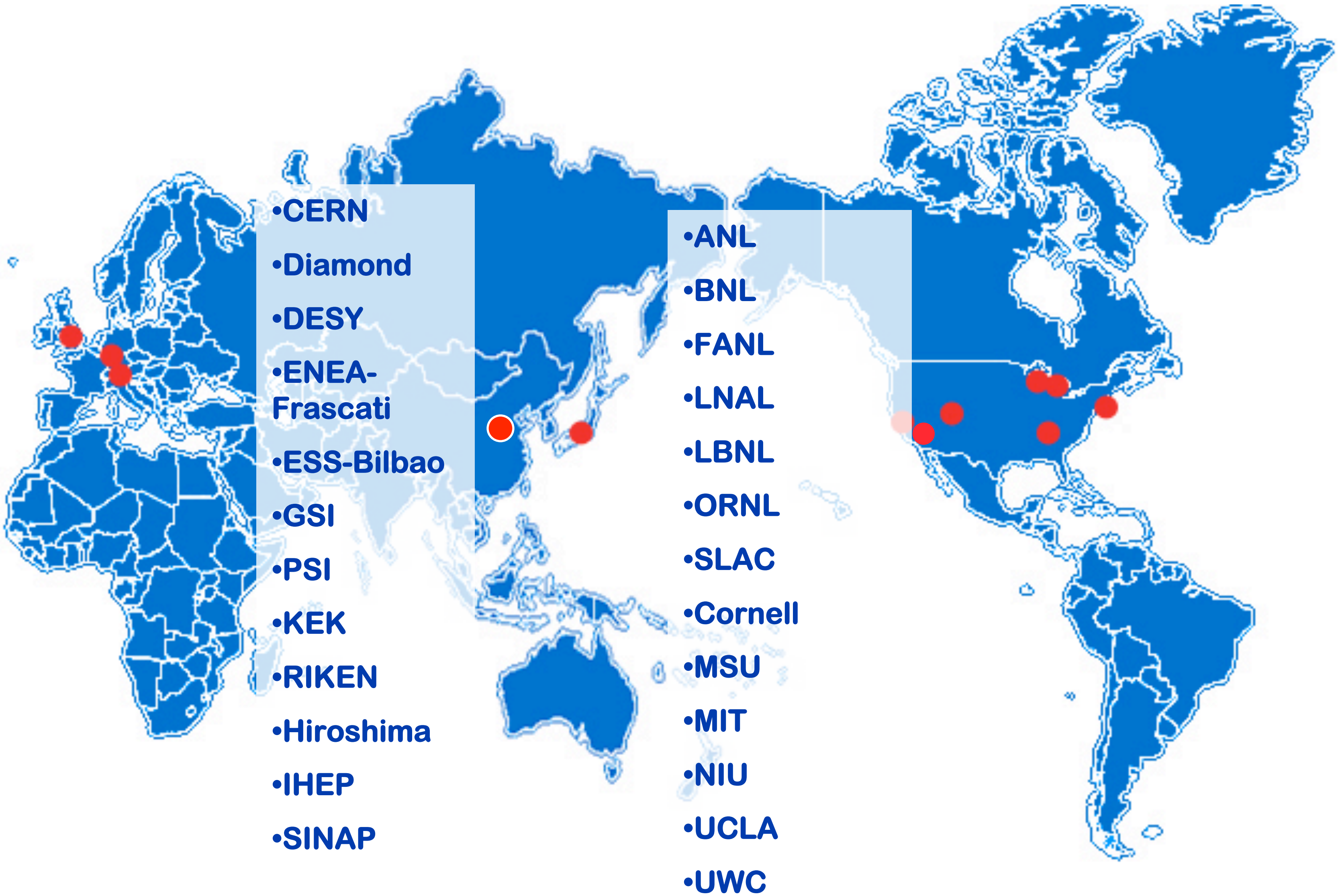


Initial current profile from direct sampling and up sampling

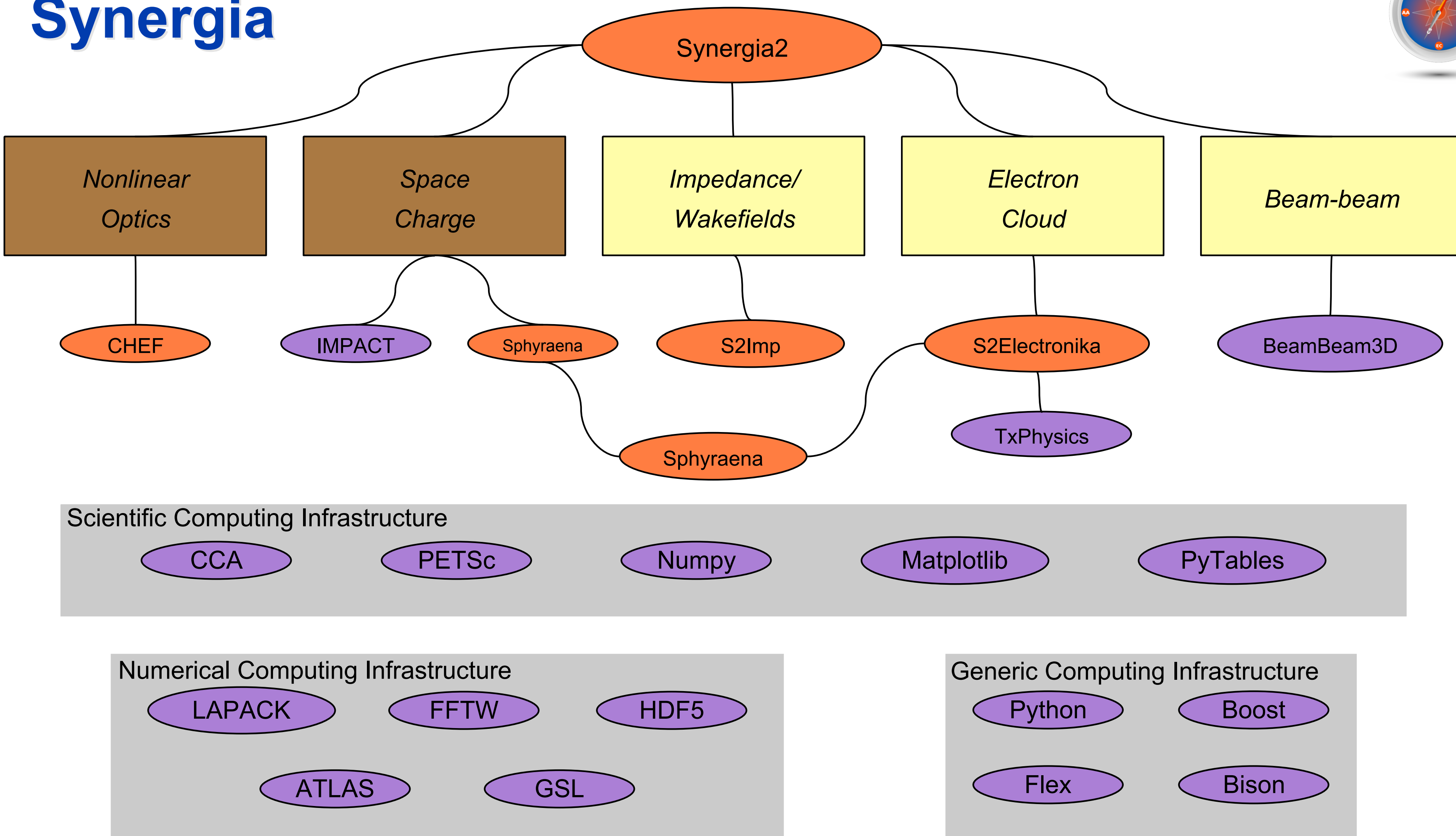


Final longitudinal phase space from direct sampling and up sampling

IMPACT Suite User-Map



Synergia



- Development is aided by relying on both internally (orange) and externally (magenta) developed state-of-the-art packages. New physics modules are currently under development.
- Applied to FNAL booster, FNAL Mu2e experiment, CERN PS2

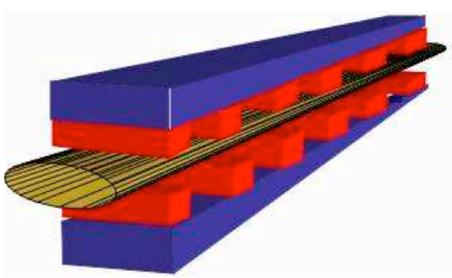
MaryLie/IMPACT (ML/I)

- Combines capabilities of MaryLie code (A. Dragt, U Md) with IMPACT code (J. Qiang, R. Ryne, LBNL) + new features
- Multiple capabilities in a single unified environment:
  - Map generation
  - Map analysis
  - Particle tracking w/ 3D space charge
  - Envelope tracking
  - Fitting and optimization
- Recent applications: ERL for e-cooling @ RHIC; CERN PS2

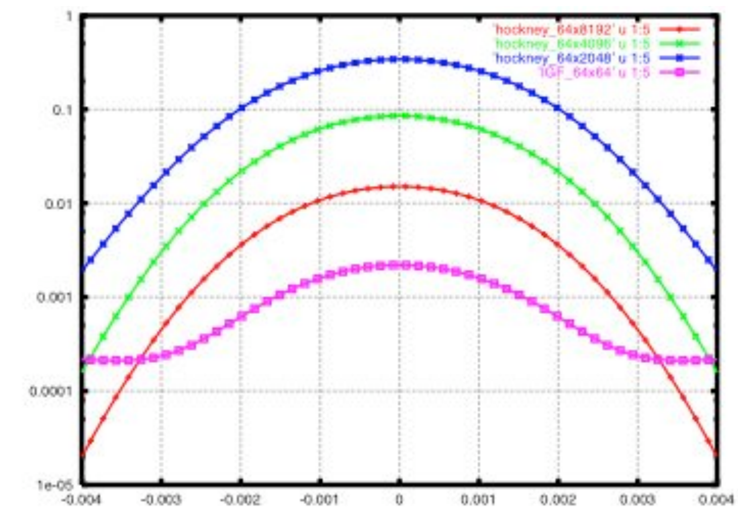
- Parallel
- 5th order optics
- 3D space charge
- 5th order rf cavity model[1]
- 3D integrated Green func[1]
- Photoinjector modeling
- Machine errors[2]
- Soft-edged magnets[2]
- Coil stacks[3]
- "Automatic" commands
- MAD-style input
- Test suite

[1]D. Abell, Tech-X
[2]V. Ranjbar, Tech-X
[3]P. Walstrom, LANL
[4]F. Neri, LANL

Map computation from surface data

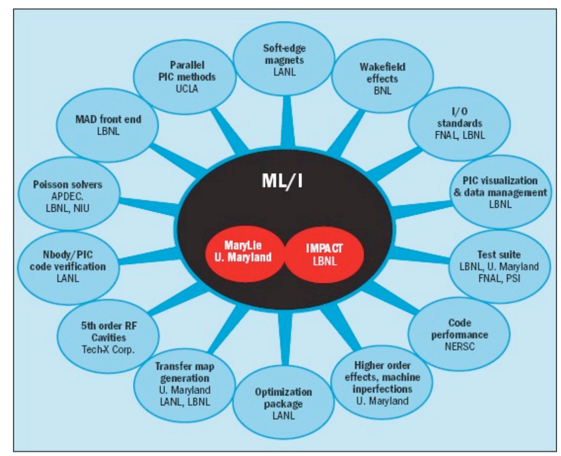


Alex Dragt, U. Md.



Error in E-field computed w/ different algorithms applied to a 2D Gaussian elliptical distribution w/ 500:1 aspect ratio

Integrated Green Function on 64x64 grid is more accurate than Hockney on 64x2048, 64x4096, 64x8192.

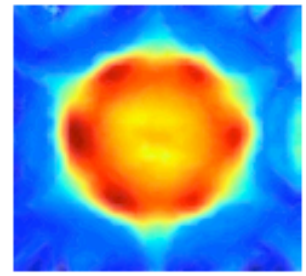


VORPAL

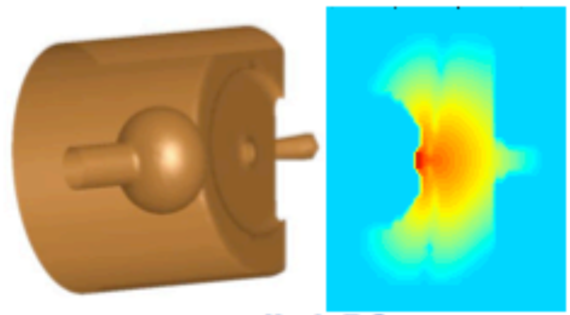
VORPAL contributes to many aspects of ComPASS beam dynamics effort

- Successfully applied to various beam dynamics domains
  - P. Stoltz *et al.*, High Brightness Workshop Proc. (UCLA, 2009), in press.
  - G. Bell, D. Bruhwiler *et al.*, J. Comput. Phys. **227**, 8714 (2008).
  - V. Litvinenko *et al.*, FEL Conf. Proc. (2008).
  - P. Messmer *et al., Particle Accel. Conf. Proc.*, 3786 *(2007).*
  - D. Dimitrov *et al., Particle Accel. Conf. Proc.*, 3555 *(2007).*
  - A. Fedotov *et al.*, Phys. Rev. ST/AB **9**, 074401 (2006).
- Generating Taylor series maps of SRF cavities for tracking
  - 3D parallel simulation is encapsulated as a phase space map
  - brings realistic SRF cavity model to beam dynamics codes
- Electromagnetic simulations of RF and DC electron guns
  - fully 3D with accurate geometry; well-tested PIC algorithms
  - field emission, secondary electron generation (dark current)
  - e- impact ionization (ion back bombardment)
- Electron cooling simulations; conventional & coherent (CEC)
  - electrostatic binary Coulomb collision algorithm
  - 3D parallel electrostatic PIC and δ-f PIC
  - friction force, e- density wakes, external fields
- Electron-cyclotron resonance (ECR) ion sources (ECRIS)
  - electrostatic & electromagnetic PIC
  - high-order (up to 7^{th}) particle shapes to suppress grid heating
  - impact ionization, charge exchange, recombination

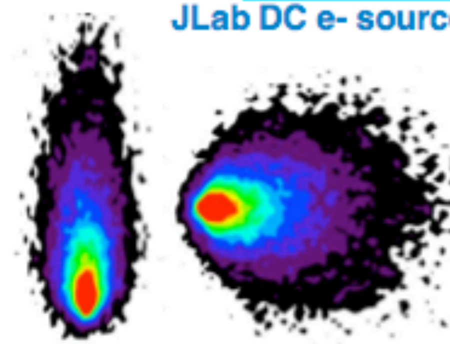
http://www.txcorp.com/products/VORPAL



e- energy distrib. in VENUS ECRIS



JLab DC e- source



e- density wake in CEC modulator

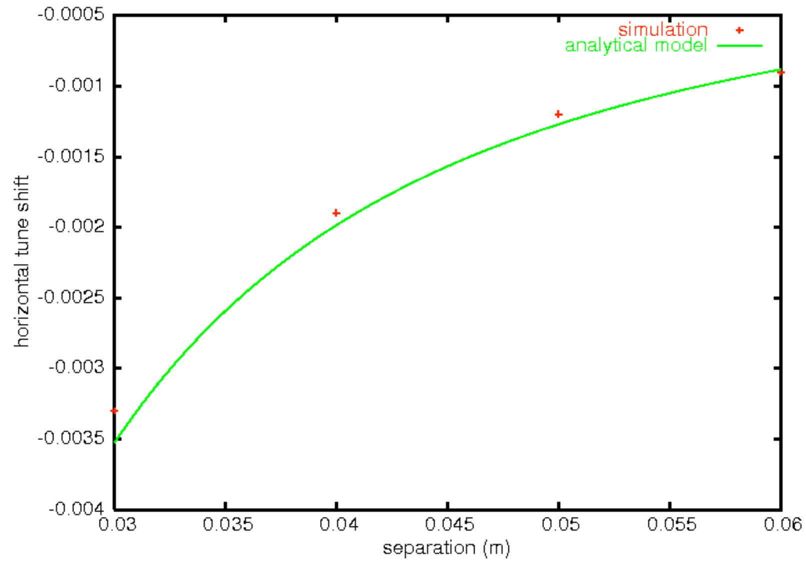
TECH-X CORPORATION

BeamBeam3D

- **Multiple physics models: strong-strong (S-S); weak-strong (W-S)**
- **Multiple-slice model for finite bunch length effects**
- **Shifted Green function -- efficiently models long-range parasitic coll**
- **Parallel particle-based decomposition to achieve perfect load balance**
- **Arbitrary closed-orbit separation (static or time-dep)**
- **Multiple bunches, multiple collision points**
- **Recent enhancements:**
  - Beam transfer function diagnostic
  - Crab cavity compensation model
  - Conducting wire compensation model
  - Footprint diagnostic
- **Applied to: Tevatron, RHIC, LHC, ELIC, eRHIC**
- **Used by researchers at FNAL and JLab**
- **Close collaboration w/ FNAL, BNL, JLab**
  - Code feedback, code enhancement

BeamBeam3D: Recent Enhancements

- Conducting wire compensation model
- Crab cavity compensation model
- Beam transfer function diagnostic
- Footprint diagnostic



Tune Shift vs. Separation from Simulated BTF Signal and Analytical Model with 50 A Compensation Wire

$$\Delta\nu_x(W) = -\frac{\mu_0}{8\pi^2(B\rho)}\beta_x\left[\frac{I_W L\ \cos 2\theta_W}{r_W^2}\right], \quad \Delta\nu_y(W) = +\frac{\mu_0}{8\pi^2(B\rho)}\beta_y\left[\frac{I_W L\ \cos 2\theta_W}{r_W^2}\right]$$

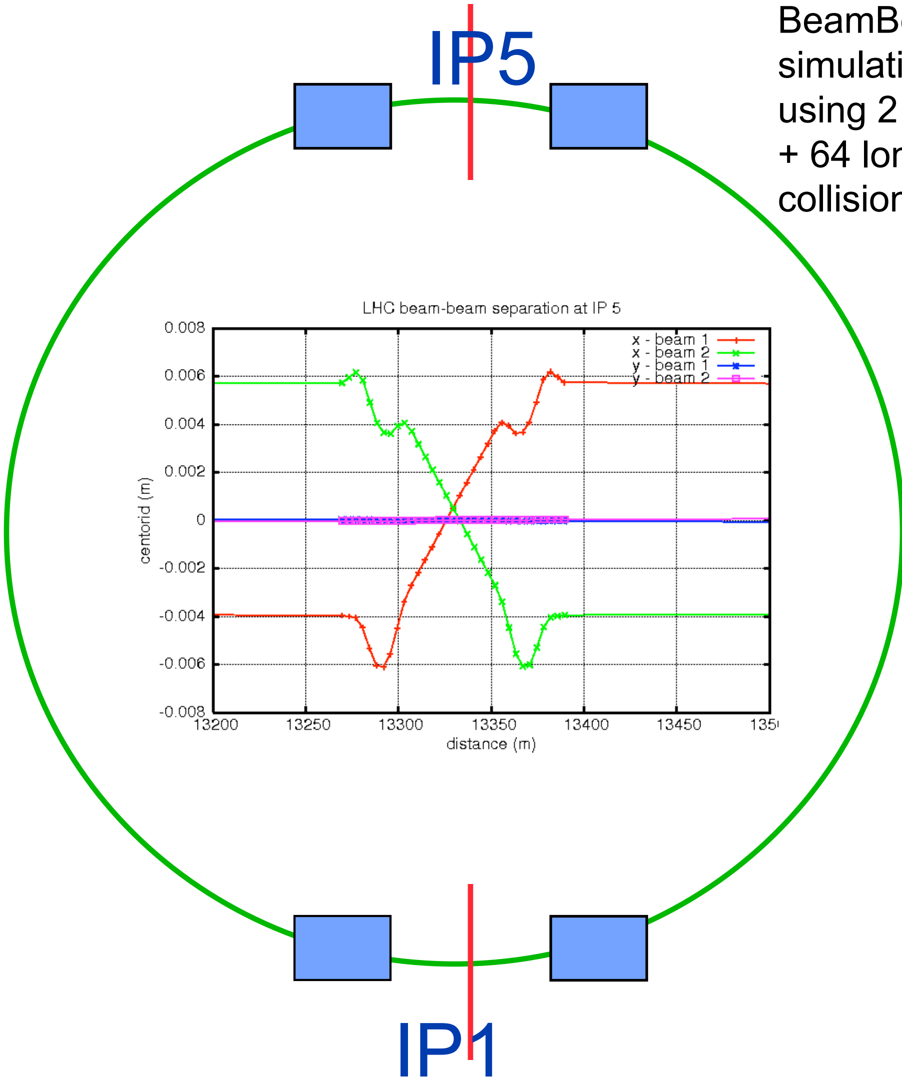
B.Erdelyi and T.Sen, "Compensation of beam-beam effects in the Tevatron with wires," (FNAL-TM-2268, 2004).

Selected Beam Dynamics Applications

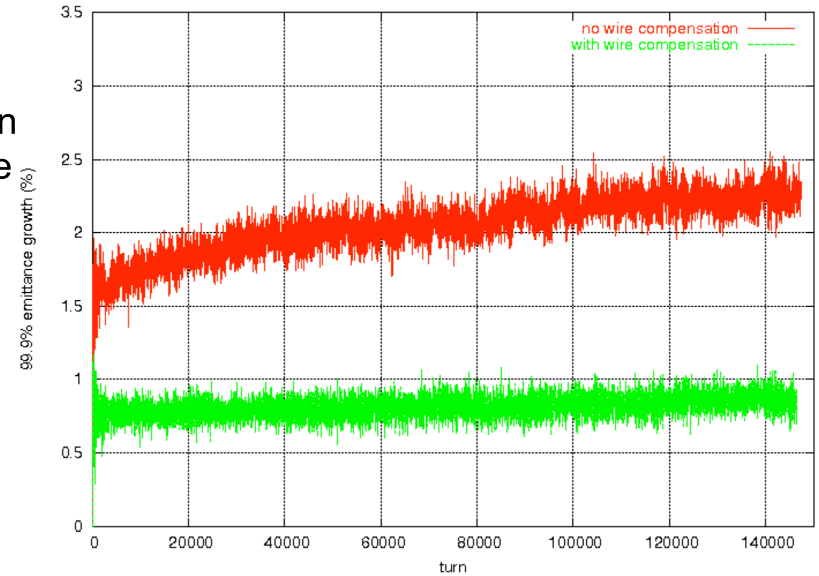
- HEP applications
  - Tevatron beam-beam simulations*
  - LHC beam-beam simulations (crab compensation, wire compensation)
  - Simulations in support of Project-X (MI resistive wall, MI e-cloud, Mu2d debuncher)*
  - ILC ring-to-main-linac; ILC damping ring*
  - Space-charge simulations of CERN PS2
  - Boosted frame technique for PWFA simulation
- NP applications
  - Beam-beam simulations in support of RHIC upgrade
  - Beam-beam simulations in support of eRHIC and ELIC
  - Electron-cooling system design
  - RIA beam dynamics
  - Transport from ECR ion source
- BES applications
  - Future light sources
- Cross-cutting applications
  - Photoinjector modeling
- Comparisons w/ experiment
  - VLEPP, LEDA, JPARC, SNS, FNAL booster

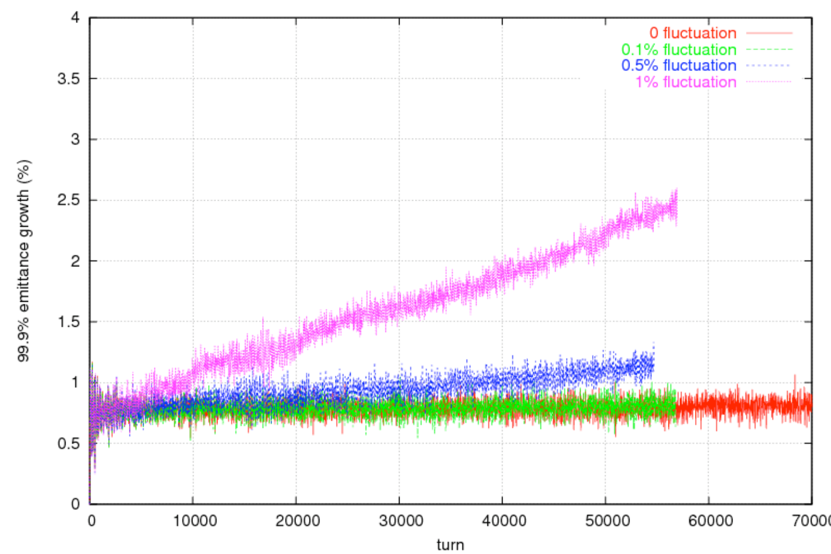
*See J. Amundson's talk

LHC wire compensation

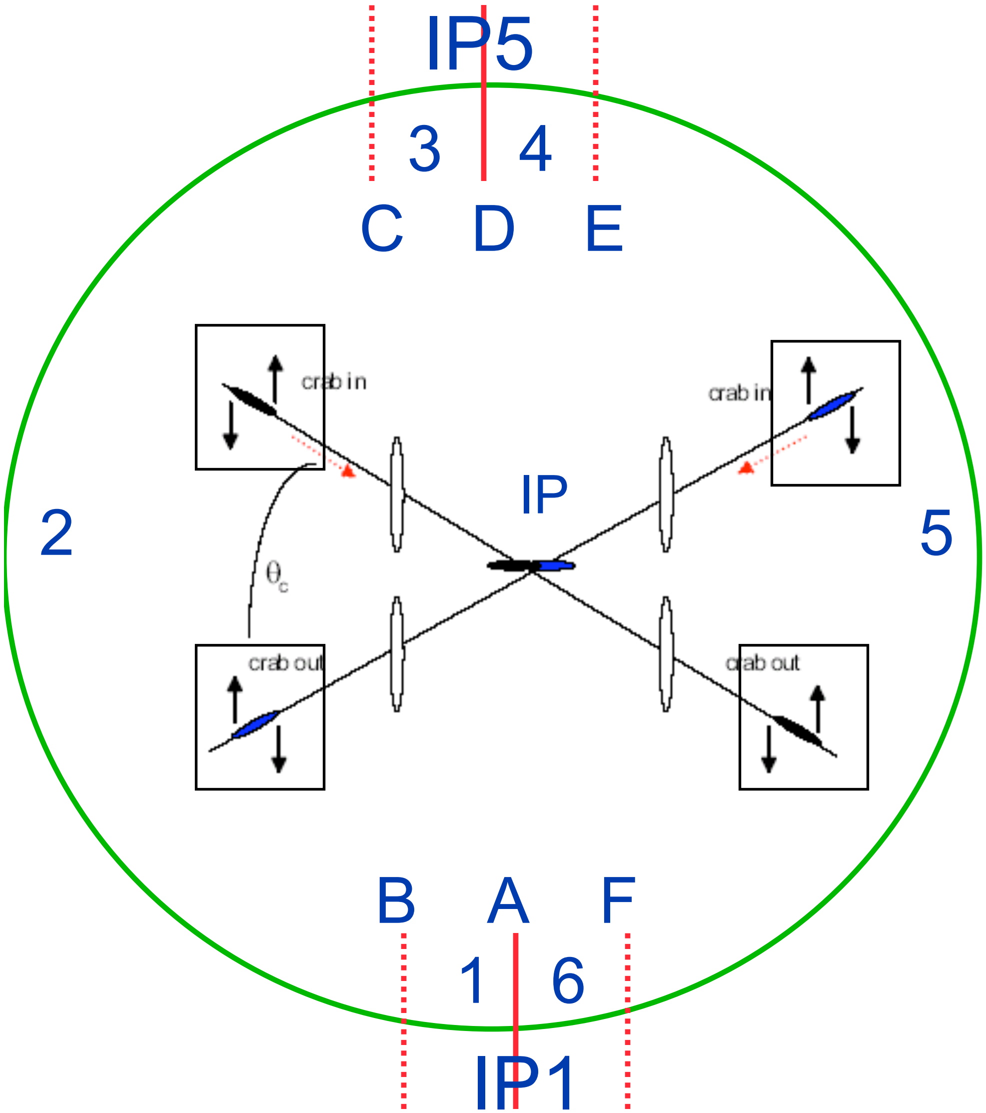


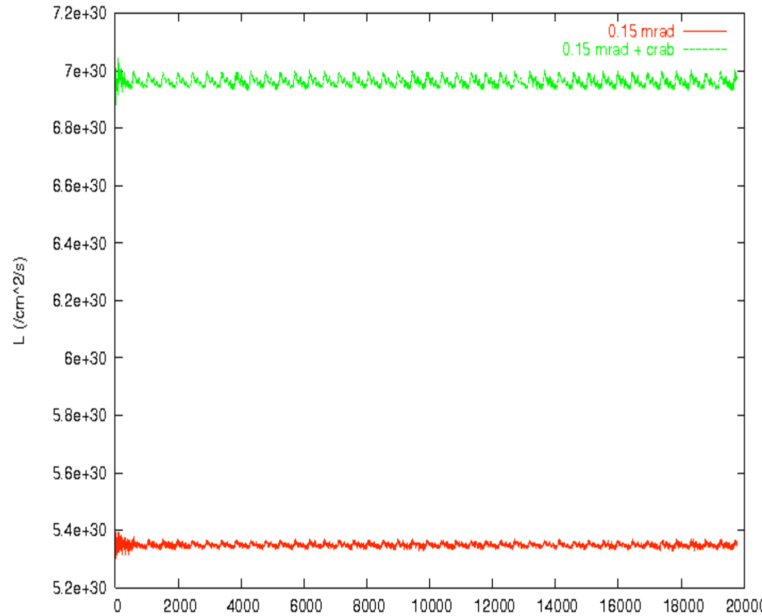
BeamBeam3d simulations using 2 head-on + 64 long-range collisions

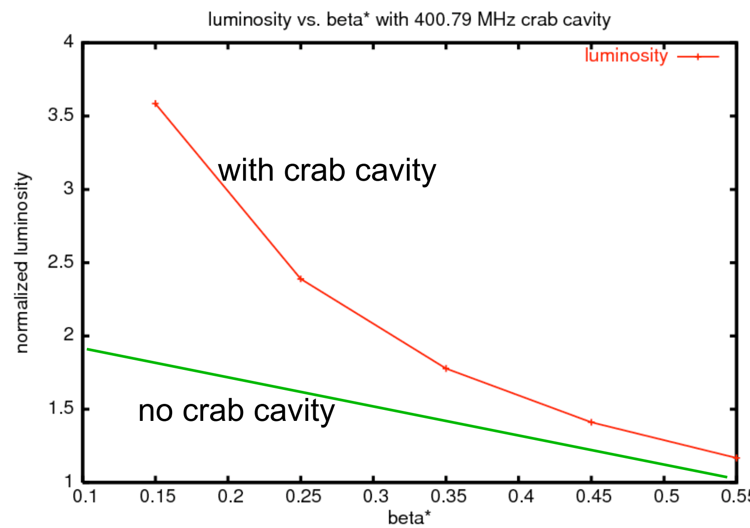




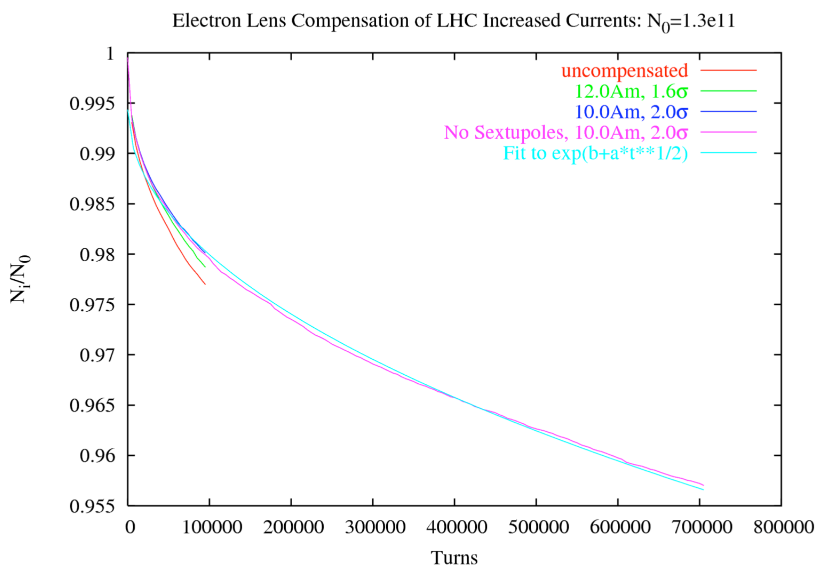
LHC Luminosity Evolution with 0.15 mrad Half Crossing Angle with/without **Crab Cavity for LHC Upgrade**







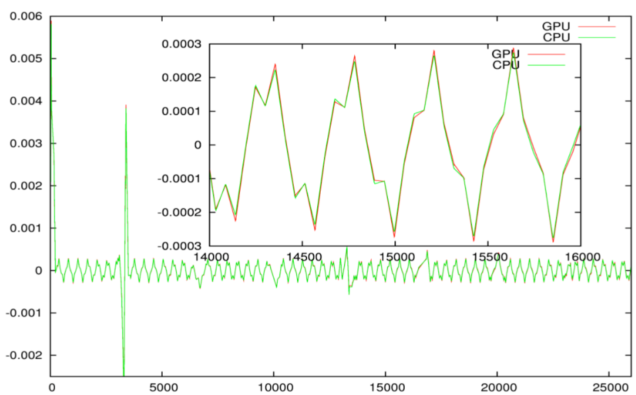
J. Qiang, LBNL



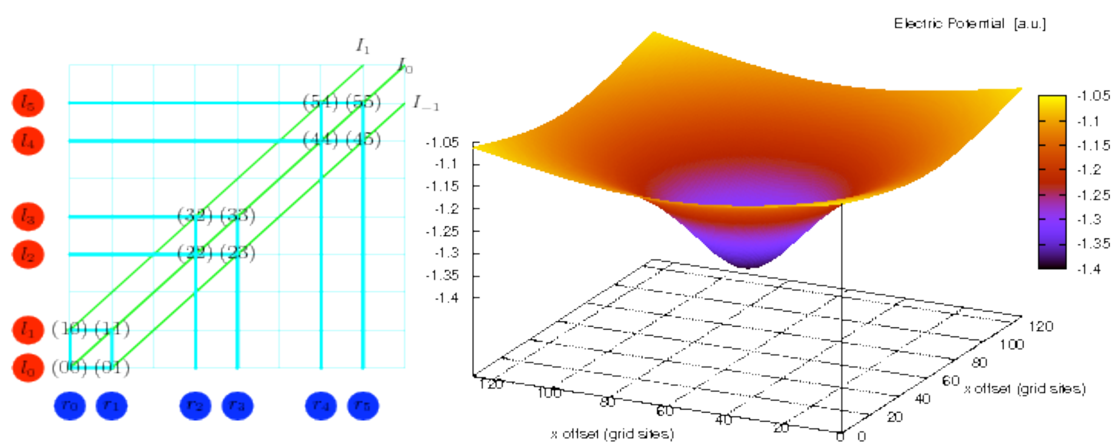
Tracking studies including all LHC beam-beam and magnetic elements reach 1 minute of accelerator time

PLIBB Tracking Code:

- Implementation of all elements necessary to track LHC
- GPU tracking module: full LHC lattice can be tracked from Nvidia GPU texture memory
- Minimally coupled parallelism scheme for multi-bunch problems; allows weak scaling for problems with realistic-sized bunch trains
- Strong-strong component using convolution-based Poisson solver



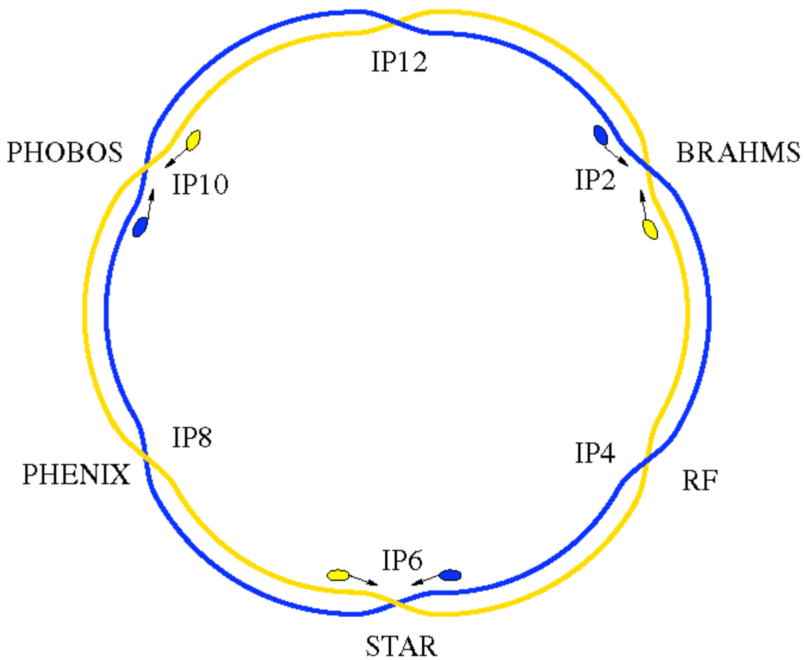
GPU Tracking module achieves 100fold speedup for tracking in magnetic elements

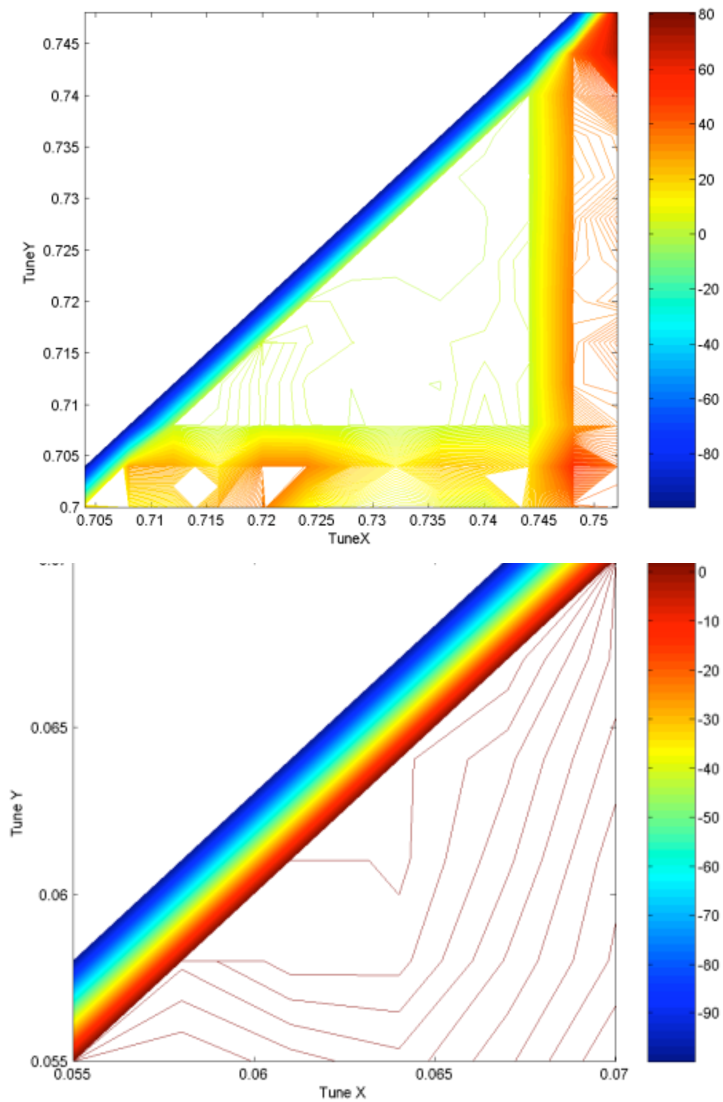


Weak scaling for multi-bunch problems:parallelism reduces to a sequence of pairwise communicators. Data exchanged can be time-dependent bunch sizes ('soft gaussian') or full solution of Poisson's equation ('strong-strong')

A. Kabel, SLAC

BeamBeam3D applied to RHIC



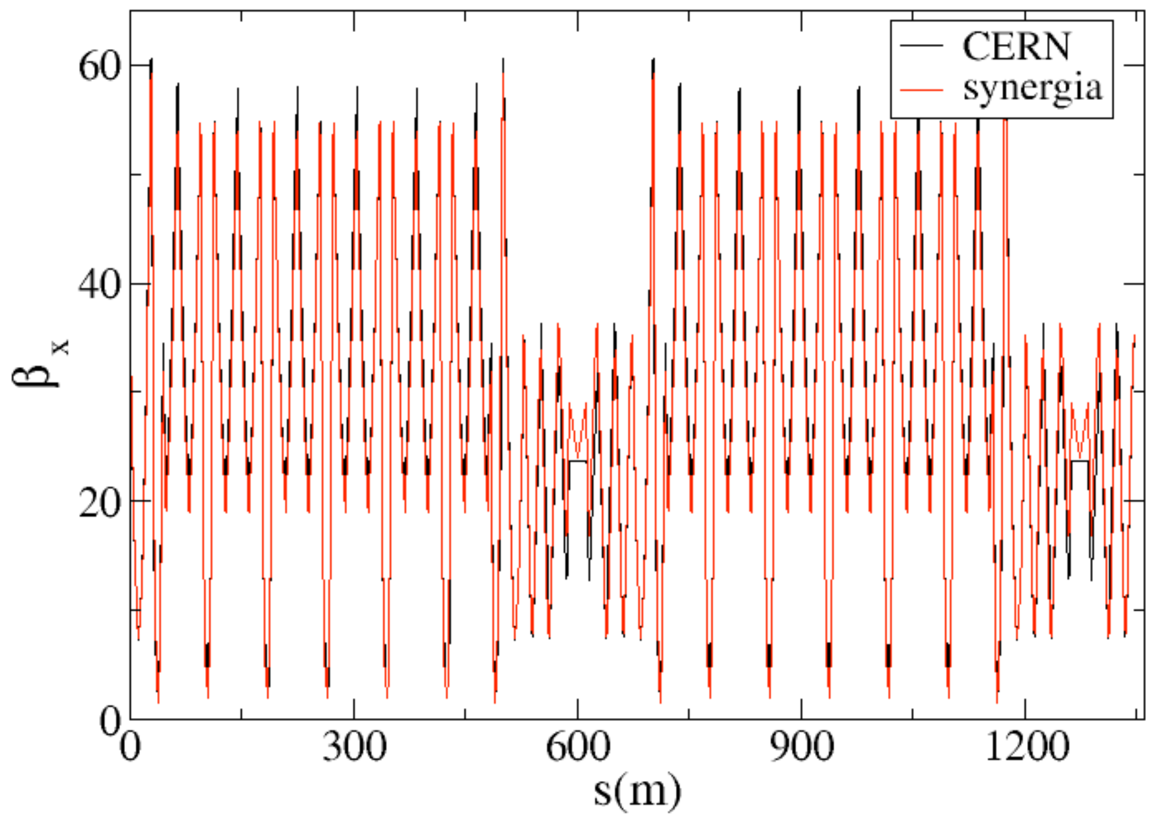


Emittance growth scan in tune space for a nominal working point (top right) and for a new working point (bottom right) at RHIC from BeamBeam3D simulation

J. Qiang, LBNL, W. Fischer, BNL

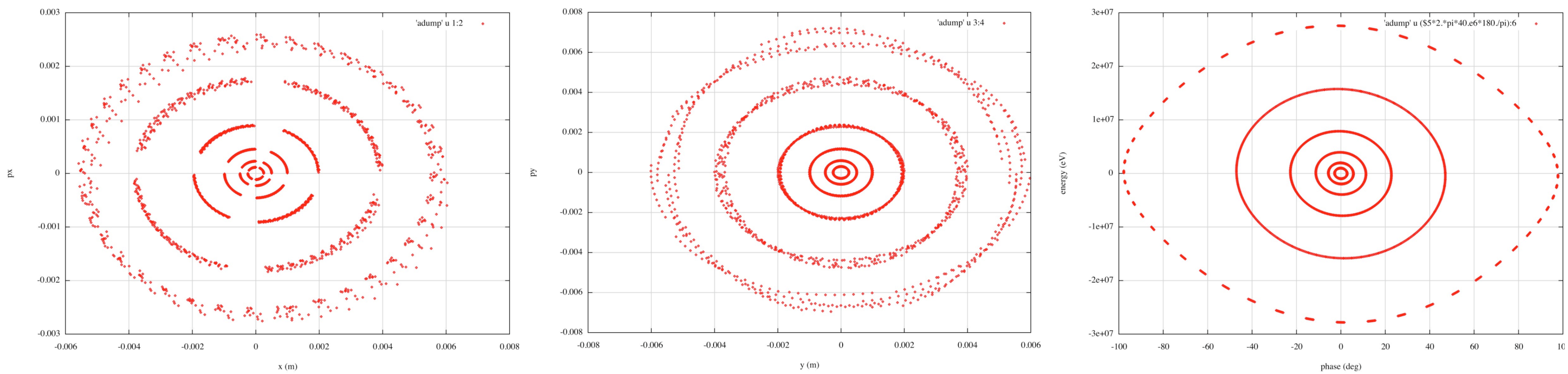
CERN PS2

- **Modelled with IMPACT-Z, Synergia, ML/I**
  - Linear lattice functions in agreement w/ CERN calculations
  - Explored dynamic aperture
  - Have begun space-charge studies



CERN PS2:
Properties in the absence of space charge

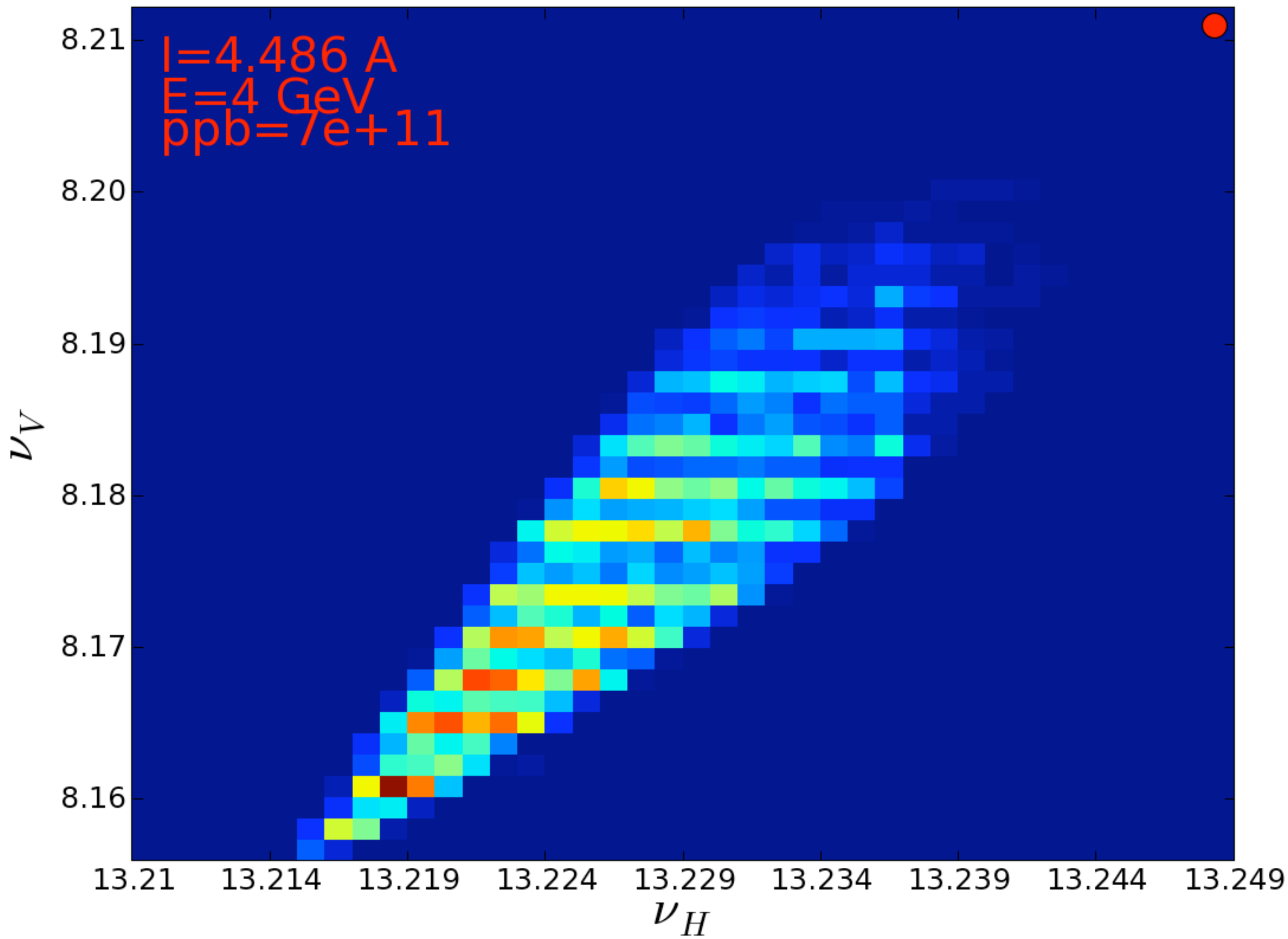
- **Used ML/I to explore nonlinear effects in the absence of space charge**
  - Single particle symplectic tracking, Poincare plots in x-px,y-py,t-pt:



- **Computed zero current match using ML/I normal form capabilities:**
  - Normalize 1-turn map: $M=A^{-1}NA$ (A= normalizing map; N=normal form)
  - Let $\zeta=(x,p_x,y,p_y,t,p_t)$ and consider a function g that depends only on $(x^2+p_x^2),(y^2+p_y^2),(t^2+p_t^2)$. Then $f(\zeta)=g(A\,\zeta)$ is a matched beam.
  - Generated macroparticle distribution, verified match

CERN PS2

- **Estimation of tune spread due to space charge**



2D simulation based on Basseti-Erskin

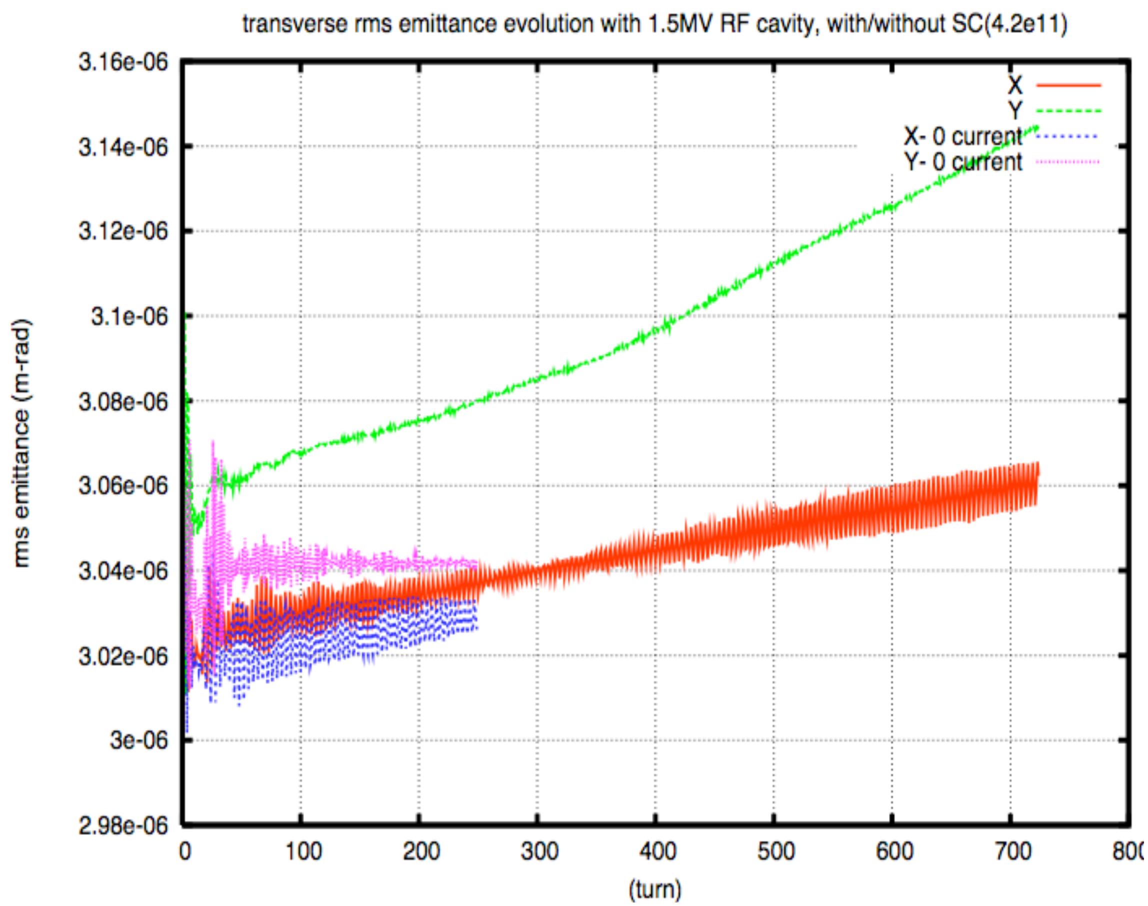
A. Macridin and P. Spentzouris, FNAL

CERN PS2: Results for zero- and finite-current tracking w/ IMPACT-Z

RF voltage: 1.5 MV
RF frequency: 40 MHz
Initial Parameters:
- kinetic energy = 4 GeV
- rms x = 1.4 mm
- rms y = 0.93 mm
- rms emittance x = 3.0 mm-mrad
- rms emittance y = 3.0 mm-mrad
- rms z = 1 ns
- rms energy spread = 9.4 MeV
- 6D Waterbag distribution

Space Charge Model:
- 60 SC kicks per turn

Aperture size:
- round pipe with 8 cm radius



J. Qiang, LBNL

Lorentz boosted frame technique

Has potential for 100x-1000x (or more) speed improvement for certain problems

3-D electron driven TMC instability (Warp-LBNL), x1000

3-D coherent synchrotron emission (Warp-LBNL), x350*

2-D laser-plasma acceleration (Warp-LBNL), x100*

1-D laser-plasma acceleration (Vorpal-Tech-X), x1,500

laser-plasma acceleration (Osiris-IST, Portugal) x150 2-D, x75 3-D

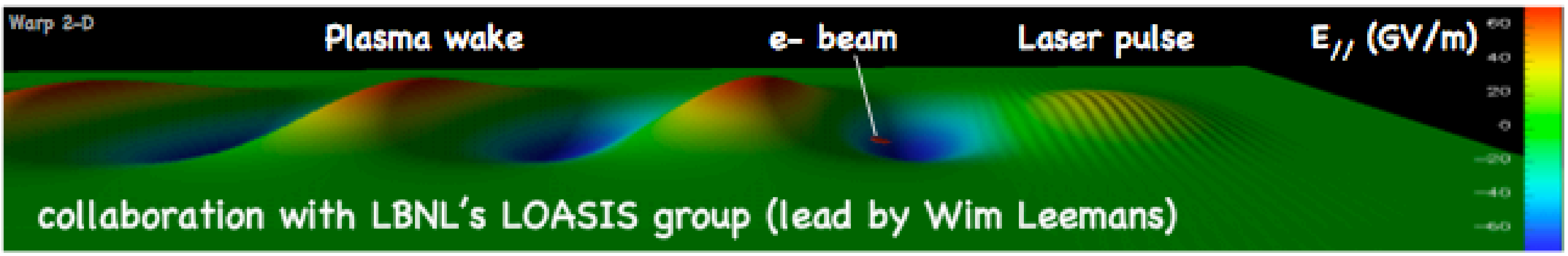
*estimated

Boosted frame example: Application to LWFA

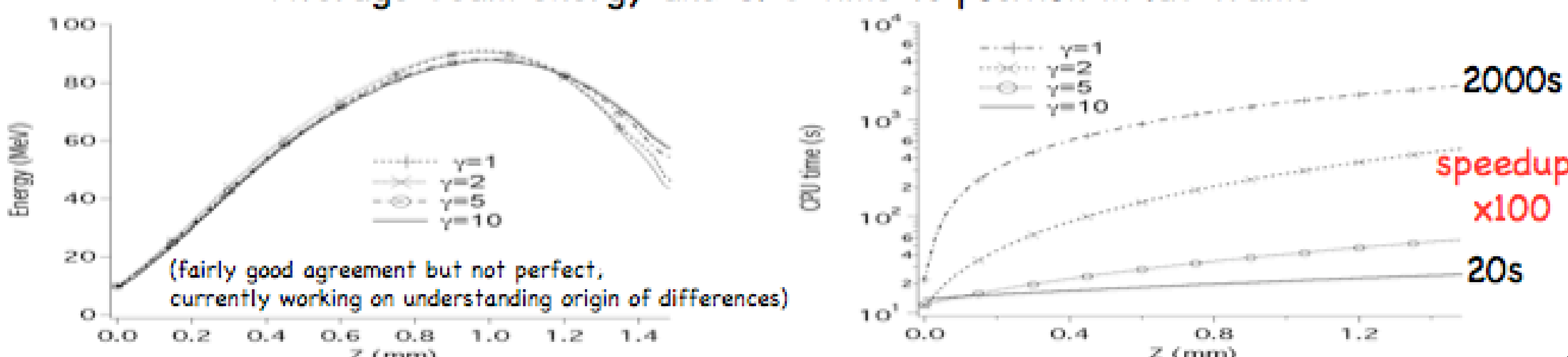
- New electromagnetic solver implemented in Warp (SBIR funding)
  - scaling test (3-D decomp)

# procs	256 (8x8x4)	512 (8x8x8)	1024 (8x8x16)
# cell, particles	$1{,}024^2\times512$, 100M	$1{,}024^3$, 200M	$1{,}024^2\times2{,}048$, 400M
Time ratio	1.	1.04	1.12

- Applied to modeling of one stage of LWFA (2-D for now, 3-D to follow)

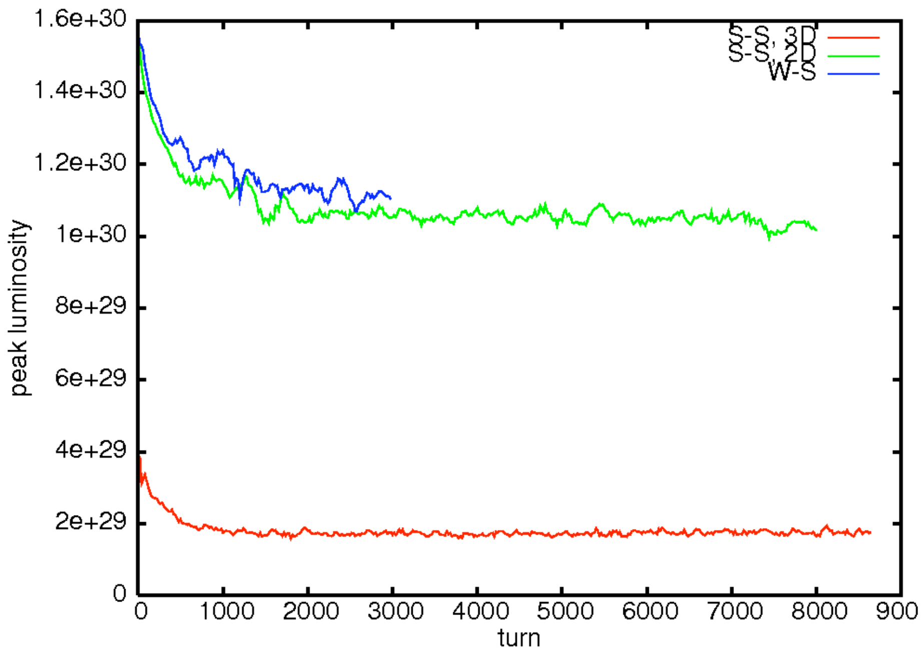


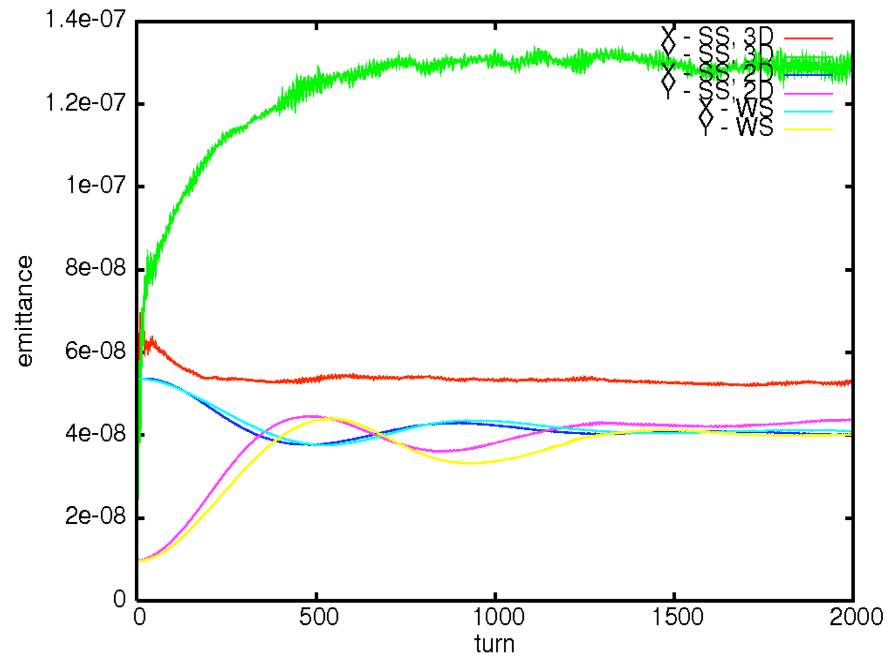
Average beam energy and CPU time vs position in lab frame



BeamBeam3D applied to eRHIC

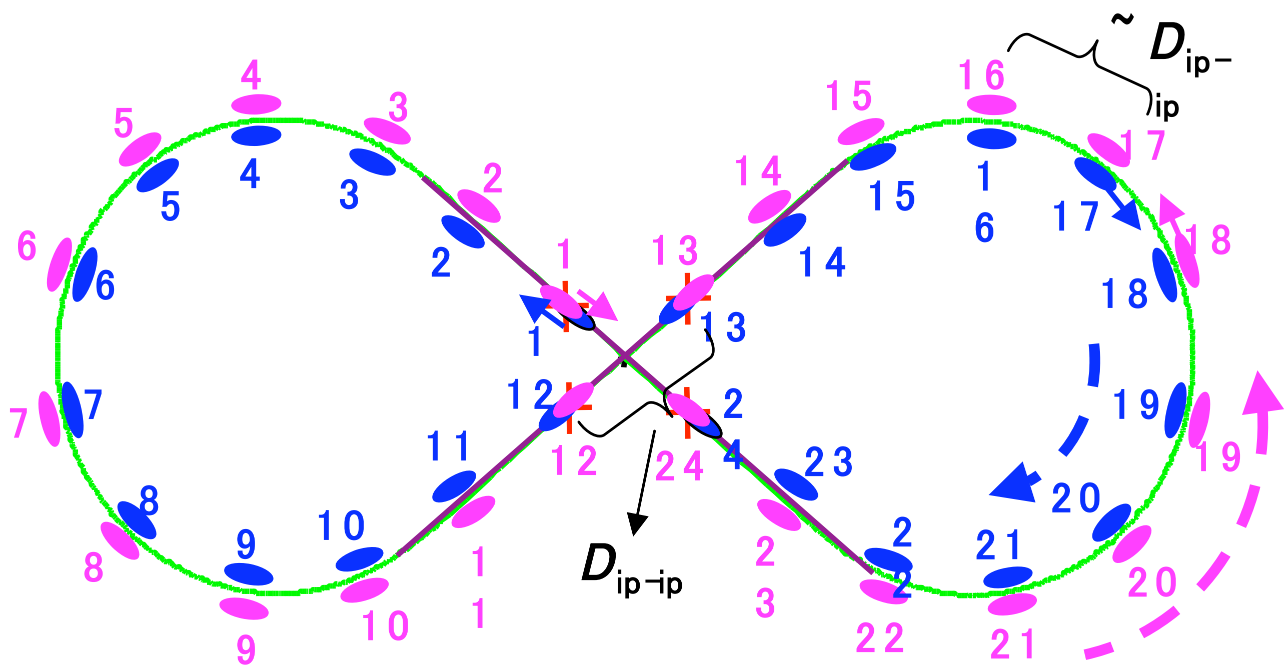
Peak luminosity and electron transverse emittances evolution at eRHIC
From S-S 3D, S-S 2D, W-S beam-beam models





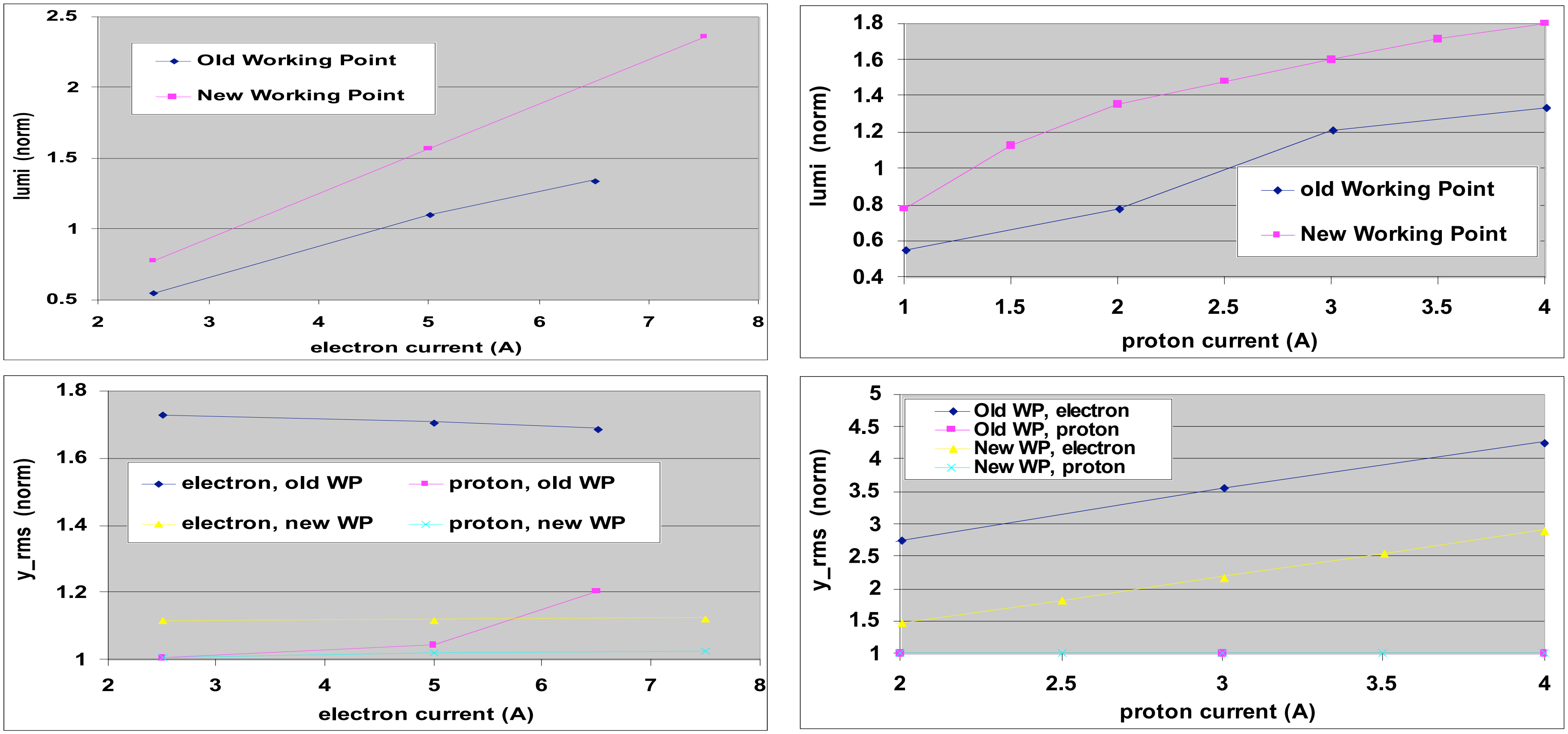
Y. Zhang, JLab

BeamBeam3D applied to ELIC



An illustration of multiple bunches colliding at all four interaction points of a Figure-8 ring

BeamBeam3D modeling of ELIC: Exploring parameter space to find improved working point

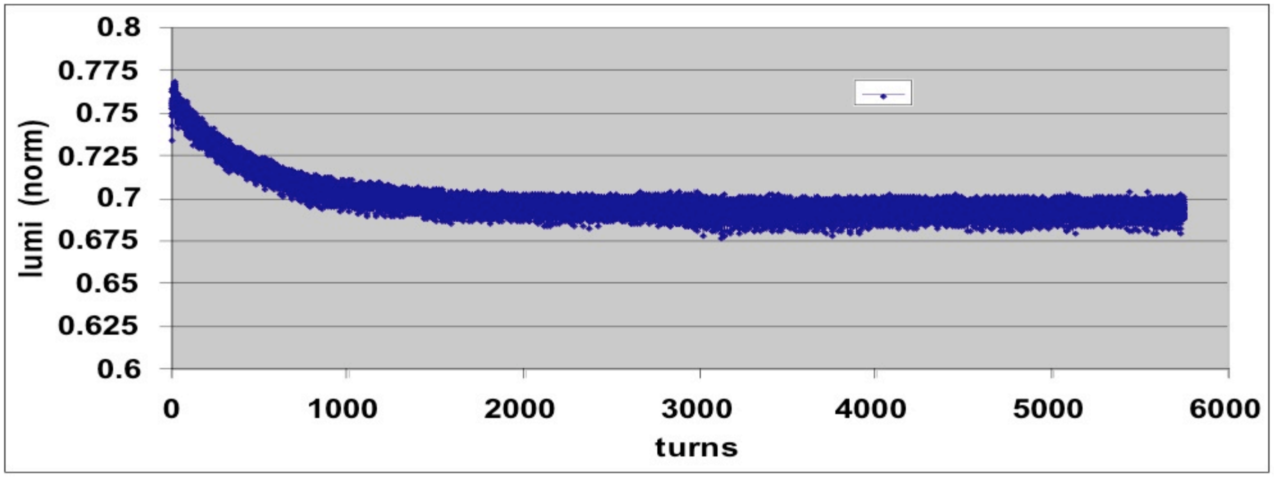


Simulation studies show

Y. Zhang, JLab

- systematic better luminosity over beam current regions with new working point,
- coherent instability is excited at same electron beam current, ~ 7 A

ELIC: Multiple IPs and Multiple Bunches



Y. Zhang, JLab

Normalized luminosity versus turns in a Figure-8 ring

- Simulated system stabilized (luminoisty, transverse size/emittance) after one damping time (more than 100k collisions)
- Luminosity per IP reaches 5.48×10^{34} $m^{-1}s^{-2}$, a 5% additional loss over hour-glass effect
- Very small additional loss due to multiple-bunch coupling
- No coherent beam-beam instability observed at ELIC nominal design parameters
- More studies (parameter dependence, coherent instability, etc.) in progress

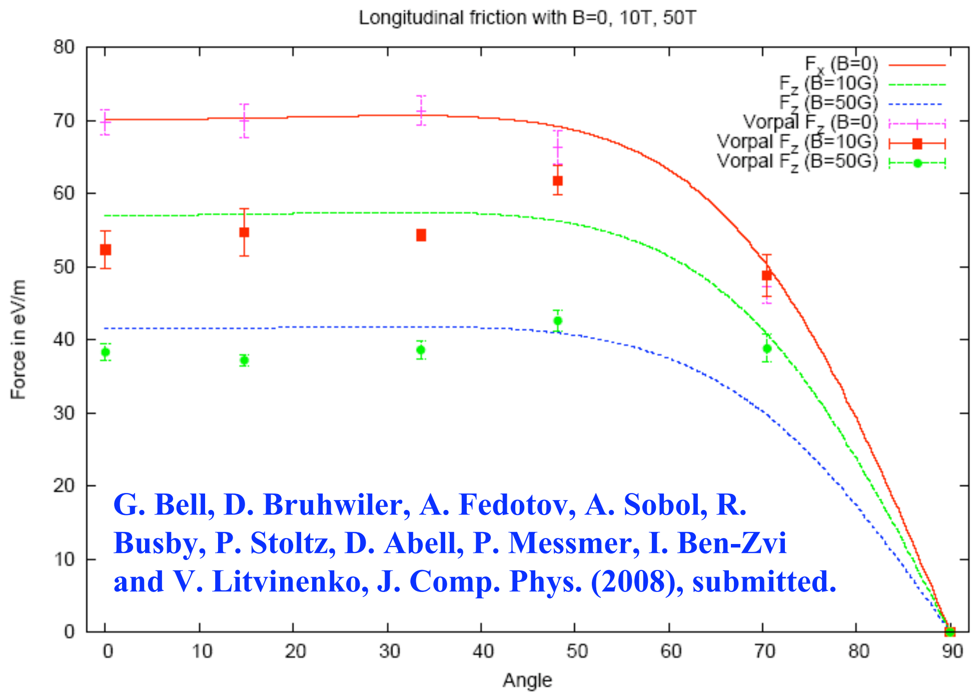
Parallel VORPAL simulations accurately calculate friction force on relativistic Au^{+79} ions in support of electron cooling designs

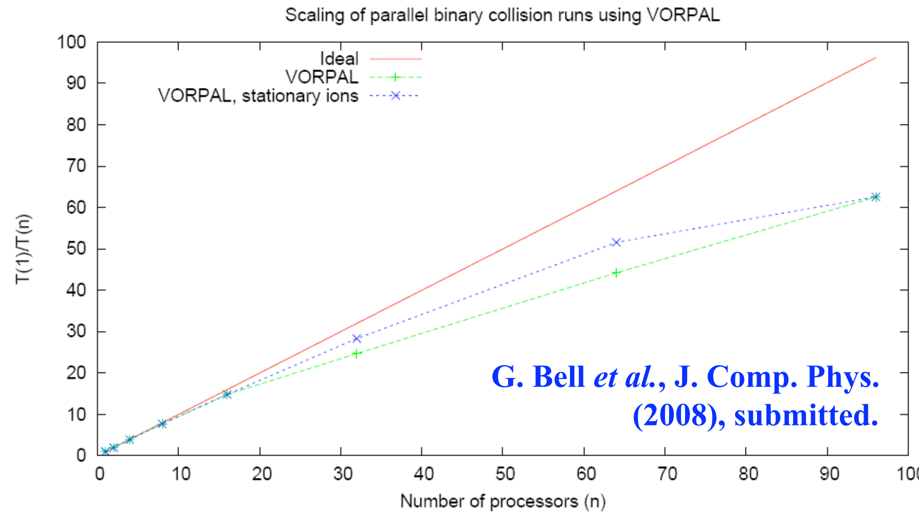
- **Electron cooling of relativistic ion beams is required for high luminosities of electron-ion collider (EIC) concepts**
  - **in the mid-term, RHIC luminosity could be increased ~10x**
    - I. Ben-Zvi *et al*., "Status of the R&D towards electron cooling of RHIC," Part. Accel. Conf. (2007).
  - **conventional wiggler could replace expensive solenoid**
    - **e- "wiggle" motion suppresses recombination with ~10 Gauss**
    - **provides focusing**
    - **reduces many technical risks**
    - **friction force should be reduced only by $\rho_{min} \rightarrow \rho_w$ in Coulomb log**
      - suggested independently by V. Litvinenko and Ya. Derbenev
      - confirmed by detailed VORPAL simulations; G.I. Bell *et al*., JCP (2008)

$$\rho_w = \frac{\Omega_{gyro}}{k_w^2 v_{beam}} \sim 1.4x10^{-3} \lambda_w^2[m] B_w[G] / \gamma$$

- **Coherent Electron Cooling concept will be simulated next**
  - **untested concept; needs 3D sim's, experimental demonstration**
    - V.N. Litvinenko and Ya.S. Derbenev, "Free Electron Lasers and High-Energy Electron Cooling," FEL'07

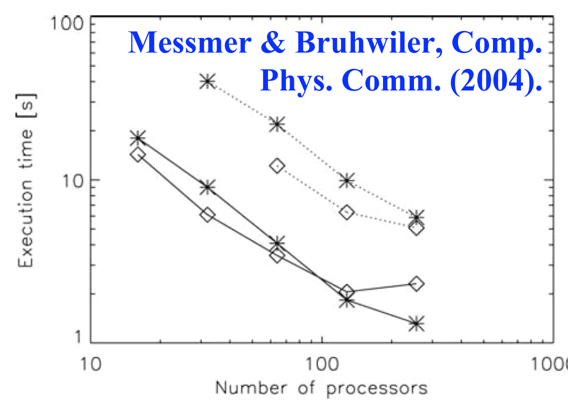
Parallel VORPAL simulations show logarithmic decrease of friction force on 100 GeV/n Au^{+79} ions in a wiggler-based e- cooler for RHIC





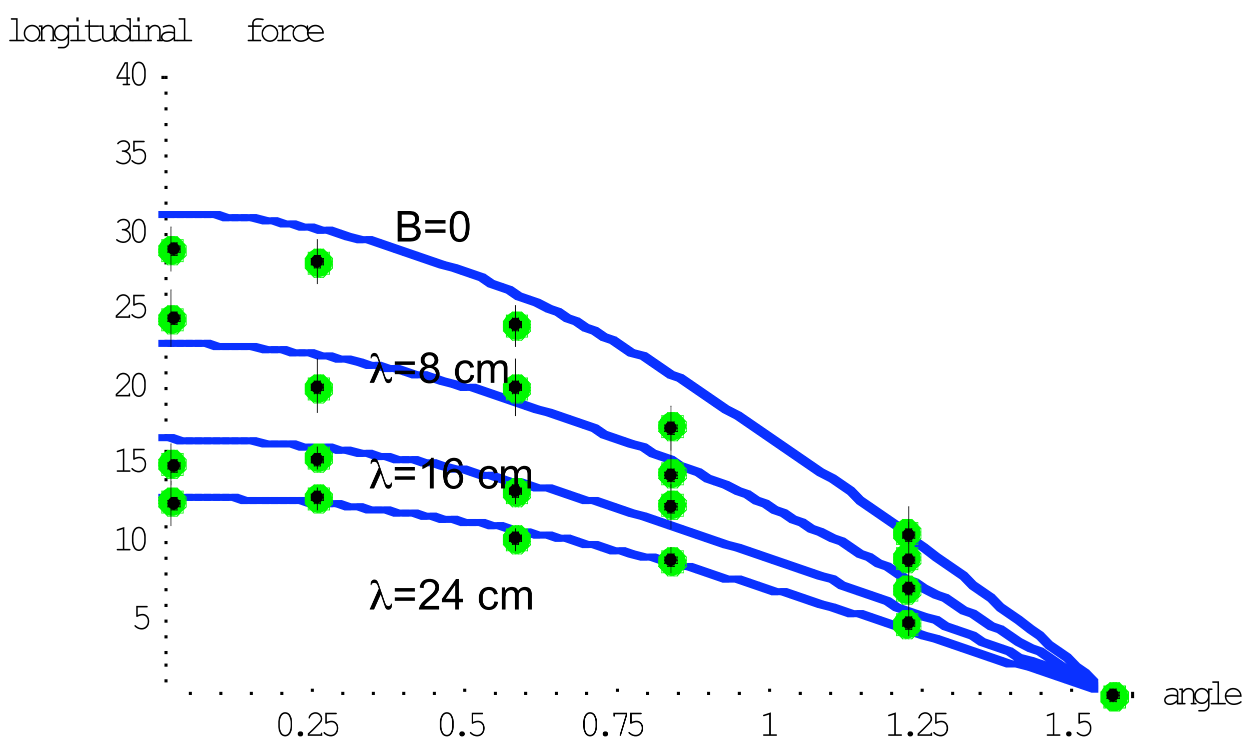
VORPAL molecular dynamics (MD) simulations of Coulomb collisions scale up to 96 proc's with 60% efficiency. A hybrid PIC/MD approach might do better.

For anticipated parameters of a RHIC e- cooler, friction force on a single Au^{+79} ion is shown as a function of the angle between the ion velocity vector and the beam axis; a modest decrease in the friction is seen, in agreement with theoretical estimates, as the wiggler field increases from 0 to 10 and 50 Gauss.



Trilinos Poisson solve for 1026×65×65 mesh (solid) & 4104×65×65 mesh (dotted), using AMG preconditioner (diamonds) vs Gauss-Seidel preconditioner (stars) for CGS.

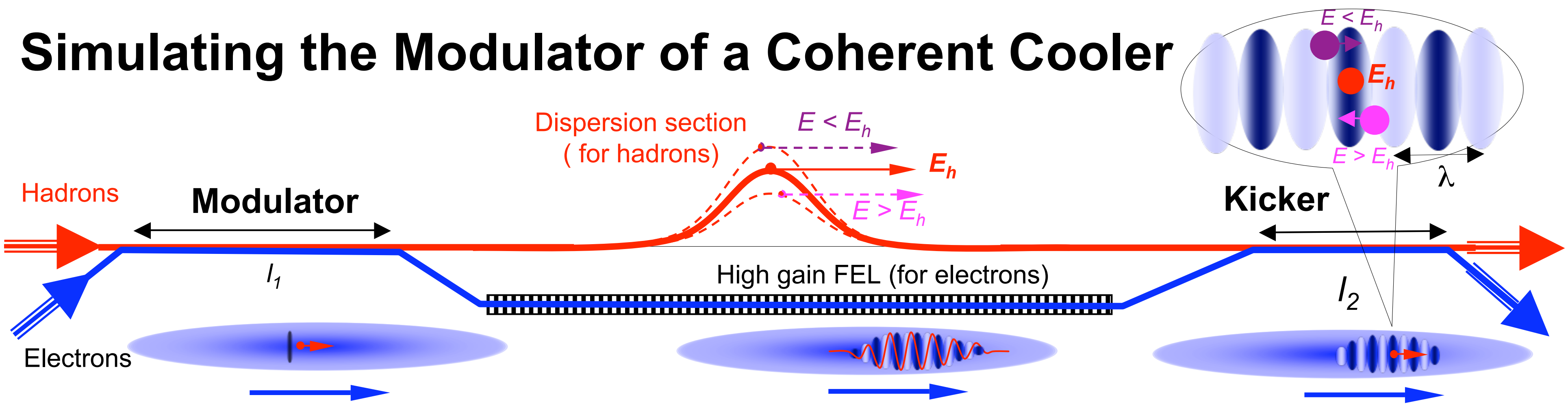
Longitudinal force in the presence of undulators fields: (B=10G, λ=8, 16, 24 cm). Curves – numeric evaluation of force integrals, dots – VORPAL simulations (Tech-X)

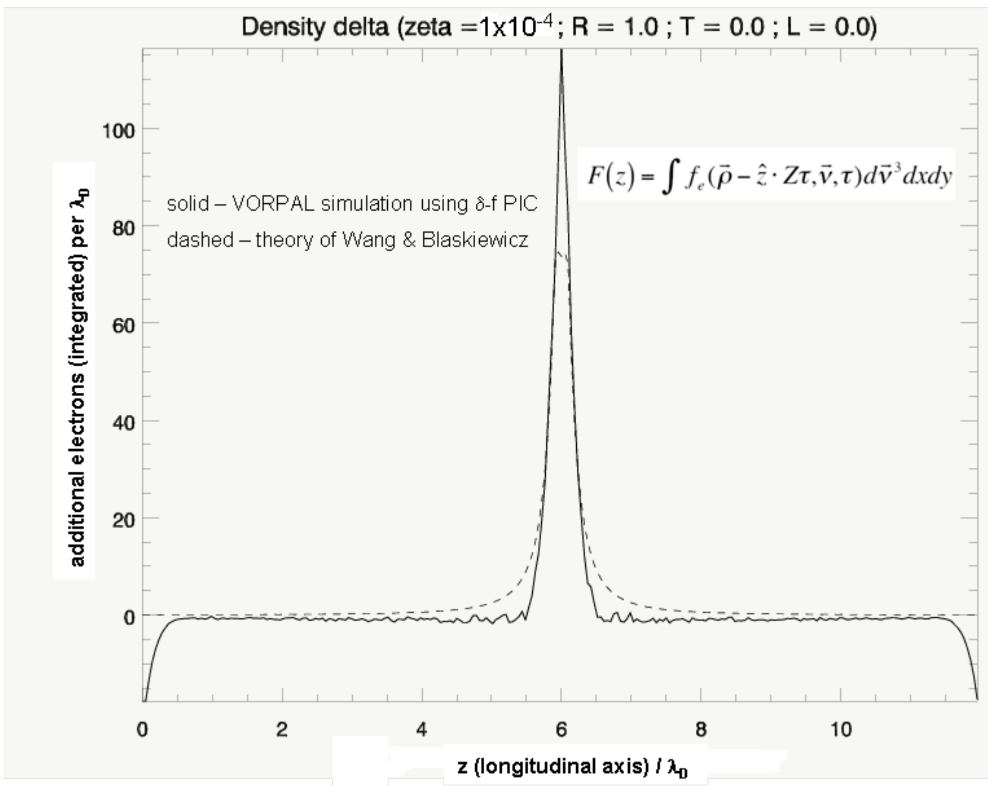


reduction in the force values as expected based on the Logarithm

Wiggler parameters:
B=10 G
λ=8, 16, 24 cm

Simulating the Modulator of a Coherent Cooler





Parallel 3D VORPAL simulations
- run on 512 Franklin cores at NERSC
- compared with theory of Wang and Blaskiewicz
- vertical axis is defined by dimensionless integral

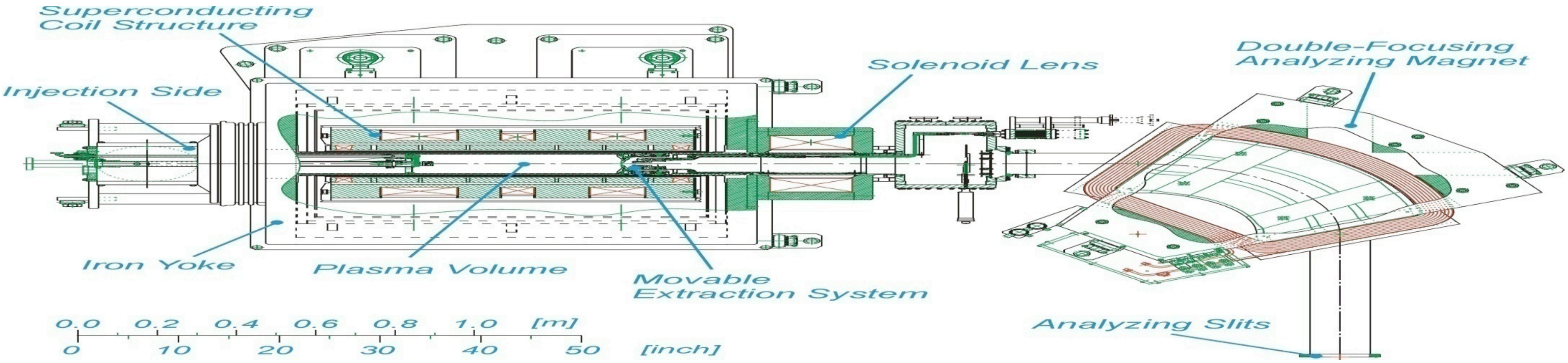
total number of electrons in simulated domain ~10^8
- dynamical response to Au+79 ion is ~100 e-'s
- relative response is 1 part in 10^6

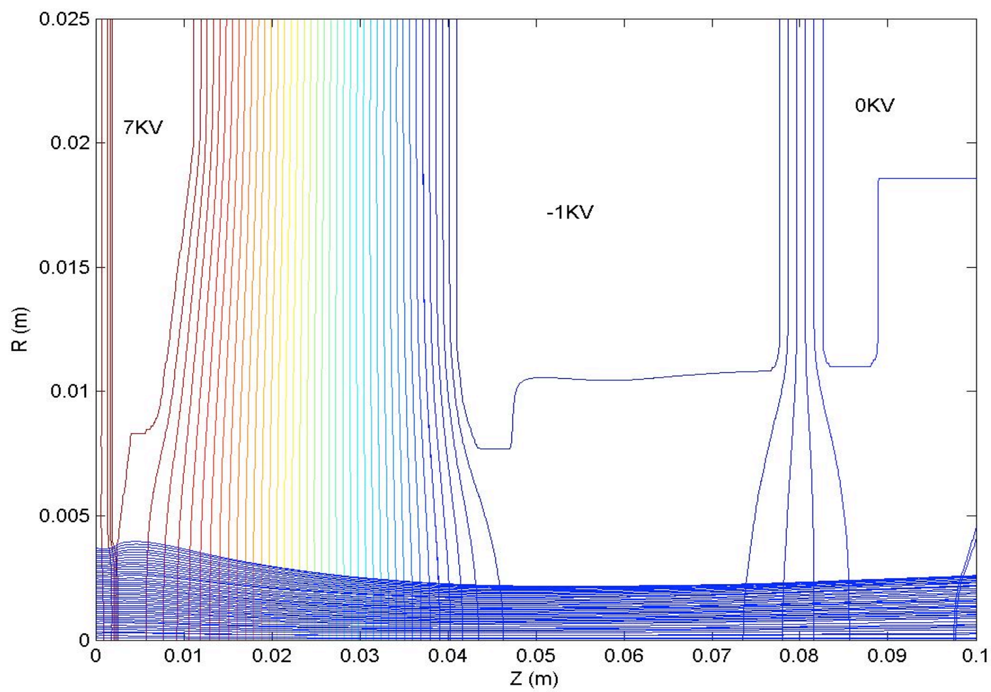
using δf PIC algorithm in VORPAL
- we capture time/space variation of the dynamics
- obtaining good agreement with theory

difficulties at the boundaries are seen
- Debye length λ_D must be well resolved
- leads to large simulations

Figure courtesy of Tech-X Corp.

IMPACT self-consistent modeling of H^+ extraction from an ECR ion source

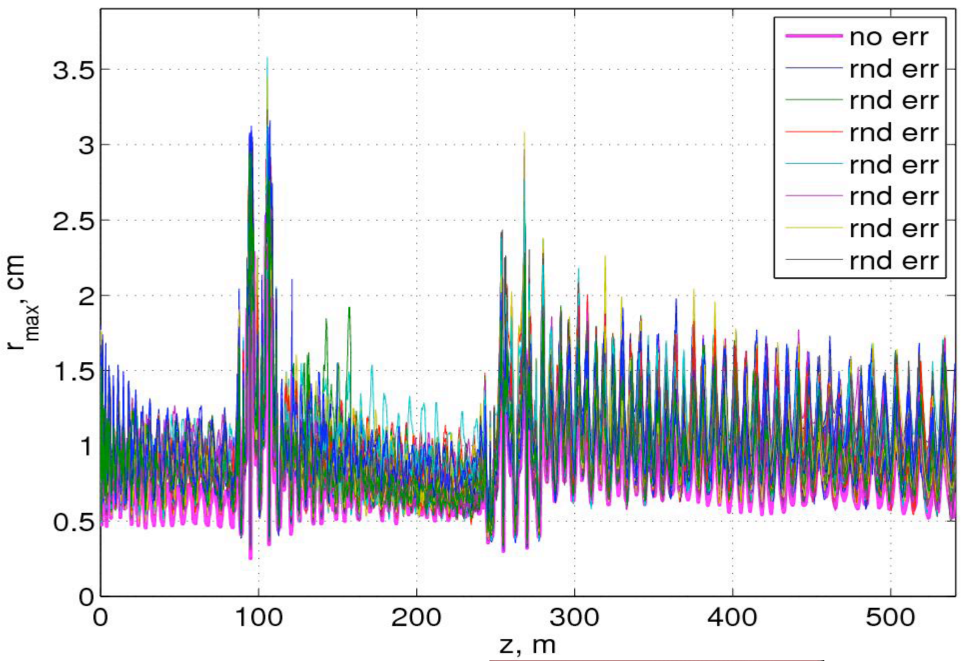


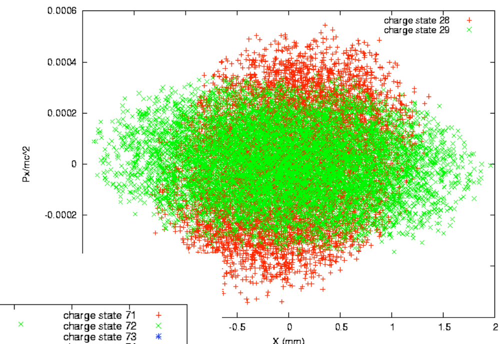


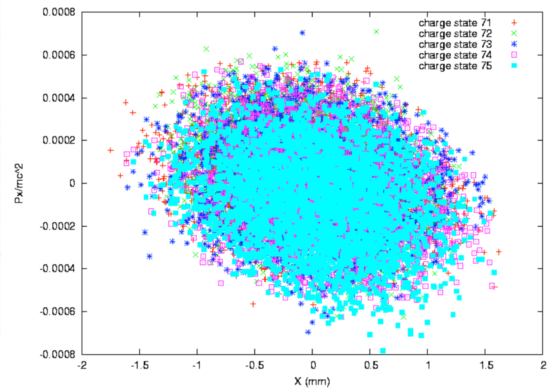
J. Qiang, LBNL

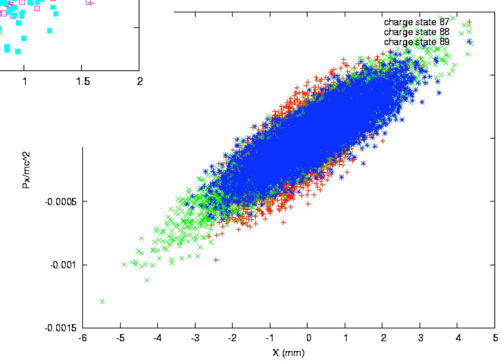
IMPACT-Z multi-charge-state simulation of beam dynamics in proposed MSU RIA linac (SciDAC+leverage)

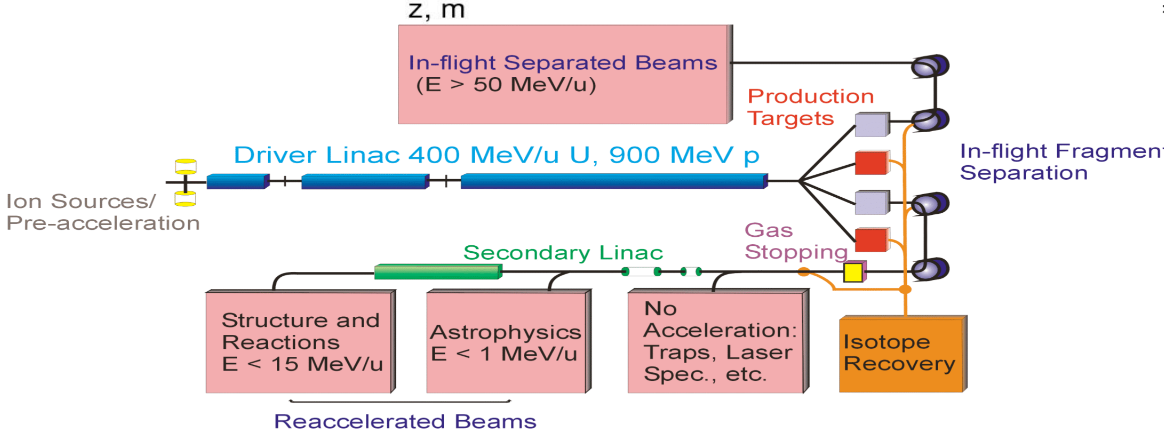
Maximum Radius Evolution with 100 Random Machine Errors





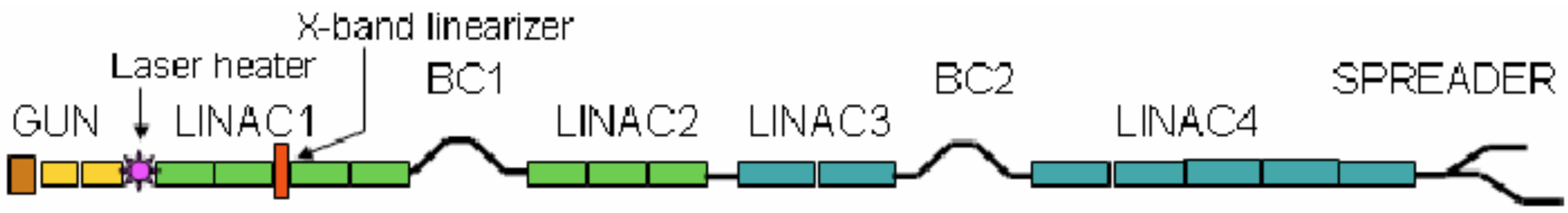


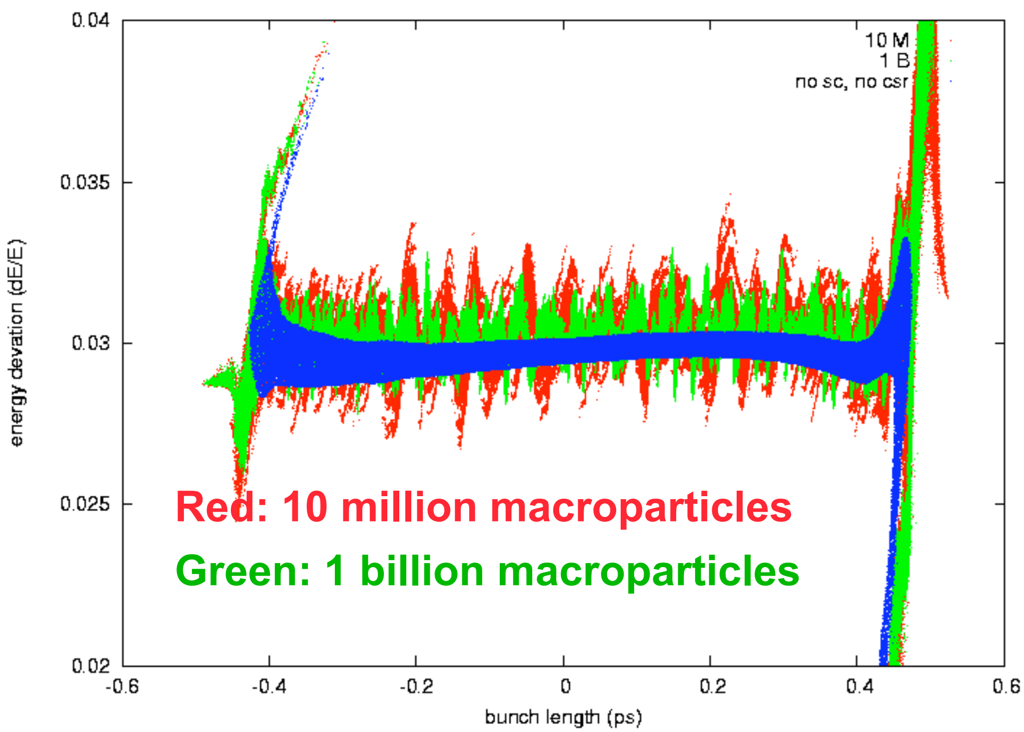




J. Qiang, LBNL

High resolution simulation of the microbunching instability using real-world # of simulation particles



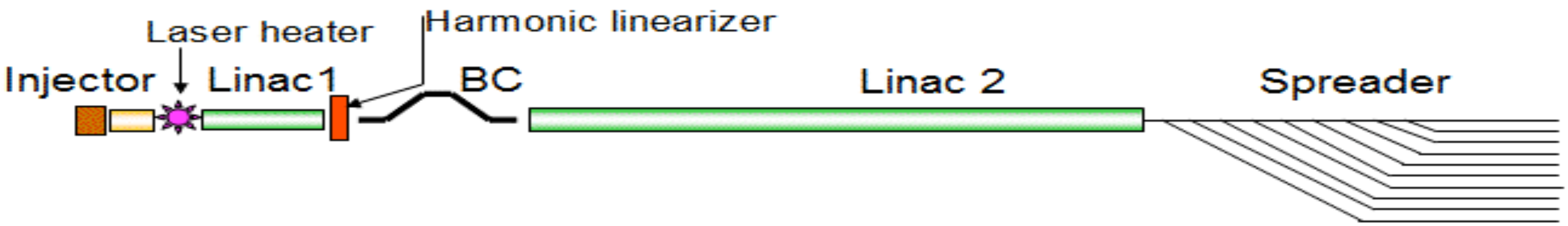


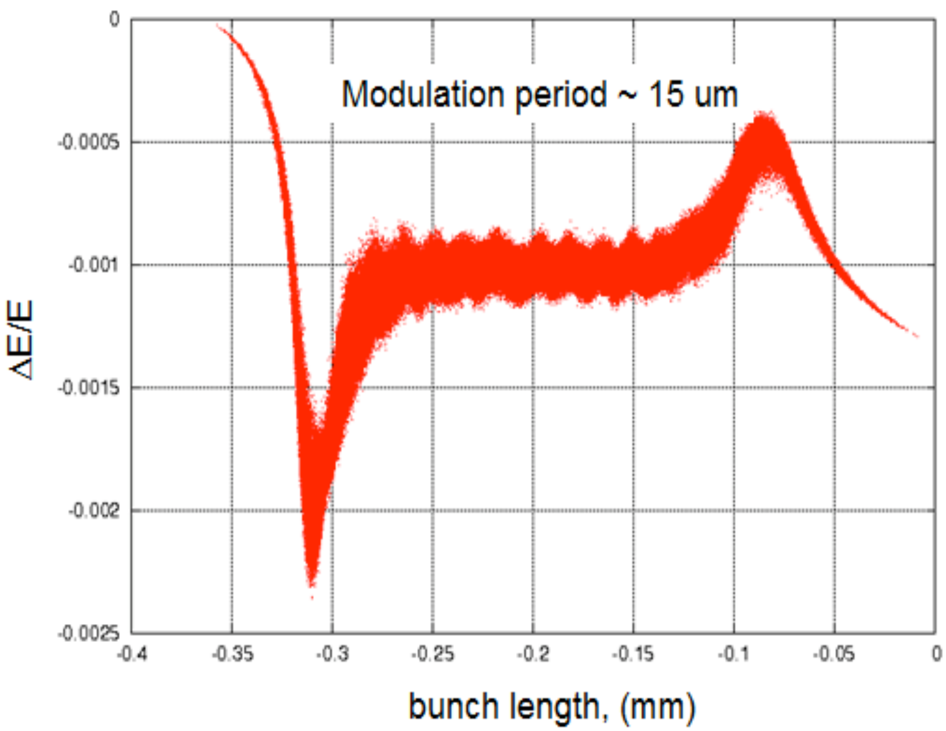
J. Qiang, LBNL

IMPACT-Z simulation showing final longitudinal phase space using 10M and 1B macroparticles

One Billion Macroparticle Simulation of an FEL Linac

(0.8 nC, from 40 MeV to 2.4 GeV, ~2 hour computing time on 512 processors)

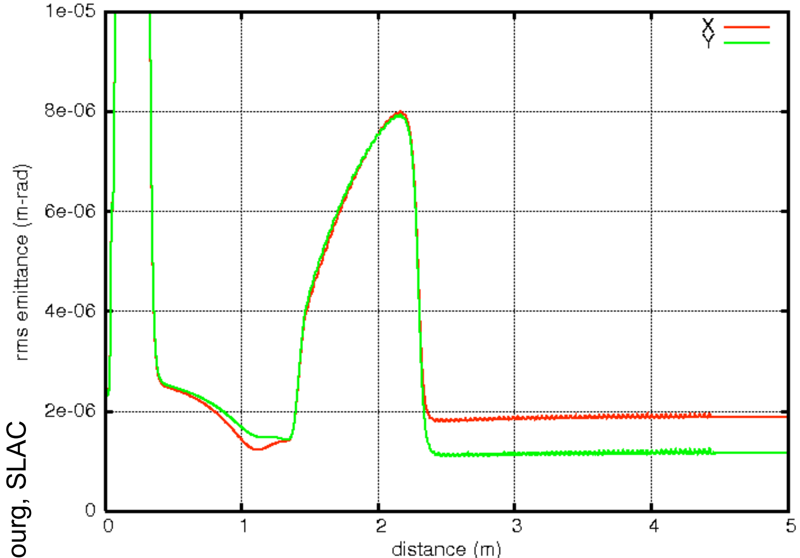




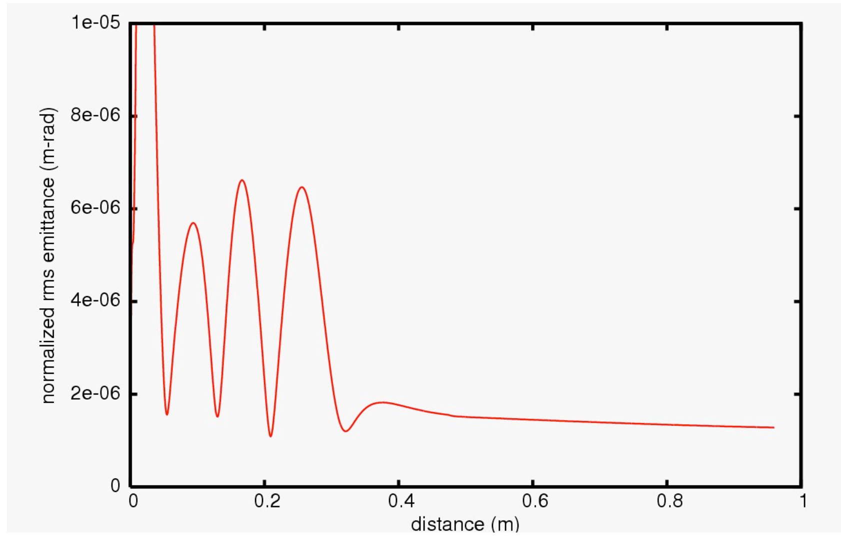
J. Qiang, A. Zholents, LBNL

Photoinjector modeling with IMPACT-T (leveraged support)

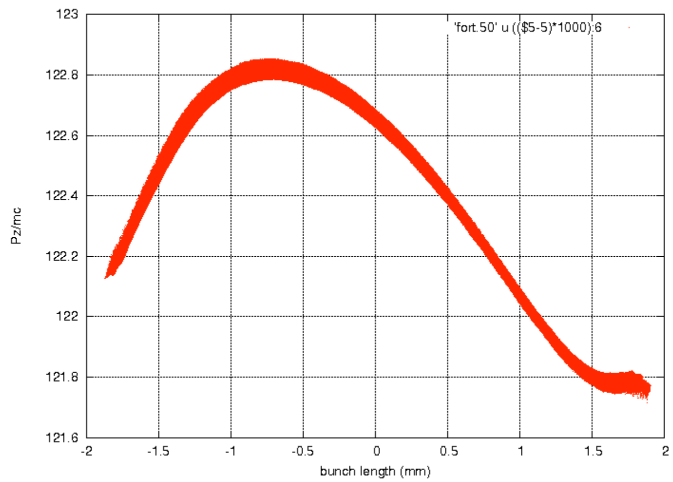
J. Qiang, LBNL, C. Limbourg, SLAC



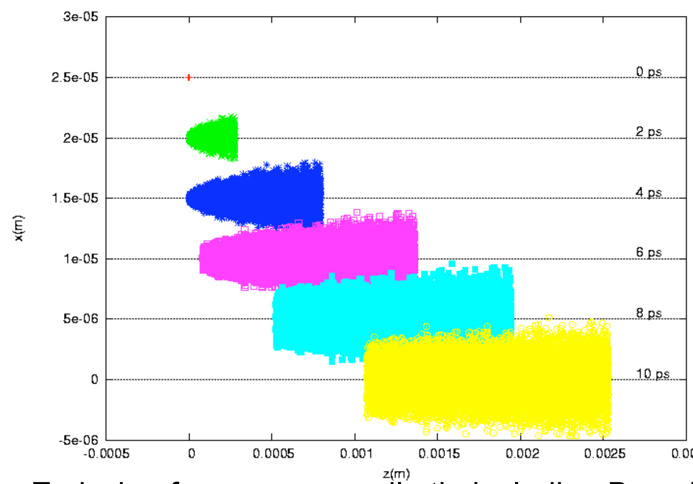
Transverse emittance evolution at LCLS photoinjector with initial 0.5 mm offset



Transverse Projected RMS Emittance vs. Distance at BNL Superconducting Photoinjector (5 MeV, 5 nC)



Longitudinal phase space at the end of LCLC photoinjector

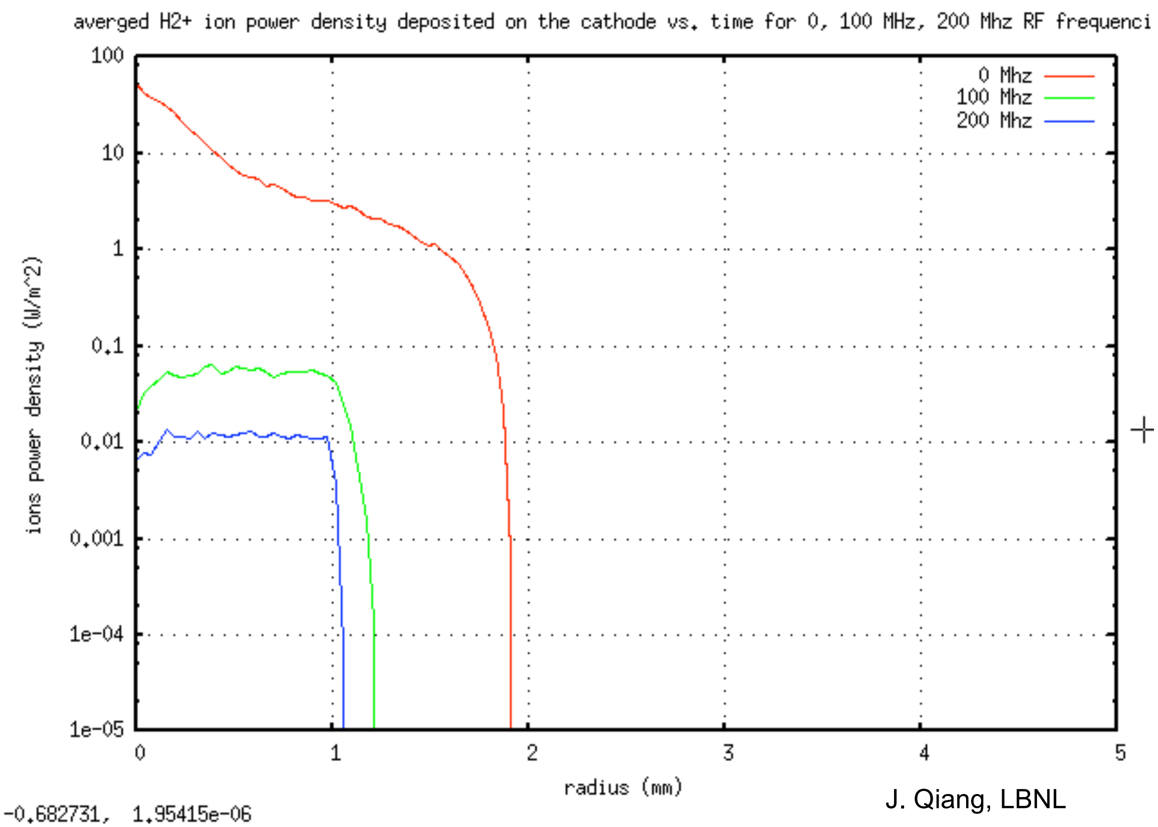


Emission from nano-needle tip including Borsch effect

PIC-Monte Carlo Simulation of Ion Back Bombardment

PIC-Monte Carlo Method:

- Electron macroparticle transport using quasi-static PIC
  - Within each time step dt, the probability of e^- ionization is:
    - $P = 1 - \exp(-n \sigma v \, dt)$
  - A uniform distributed random number R is generated:
    - If R < P, ionization occurs and an ion macroparticle is generated
  - Neglect ionization collision effects on electrons
  - Ion momentum distribution assumed to be Gaussian with given gas temp
  - Null sampling for ionization (in progress)



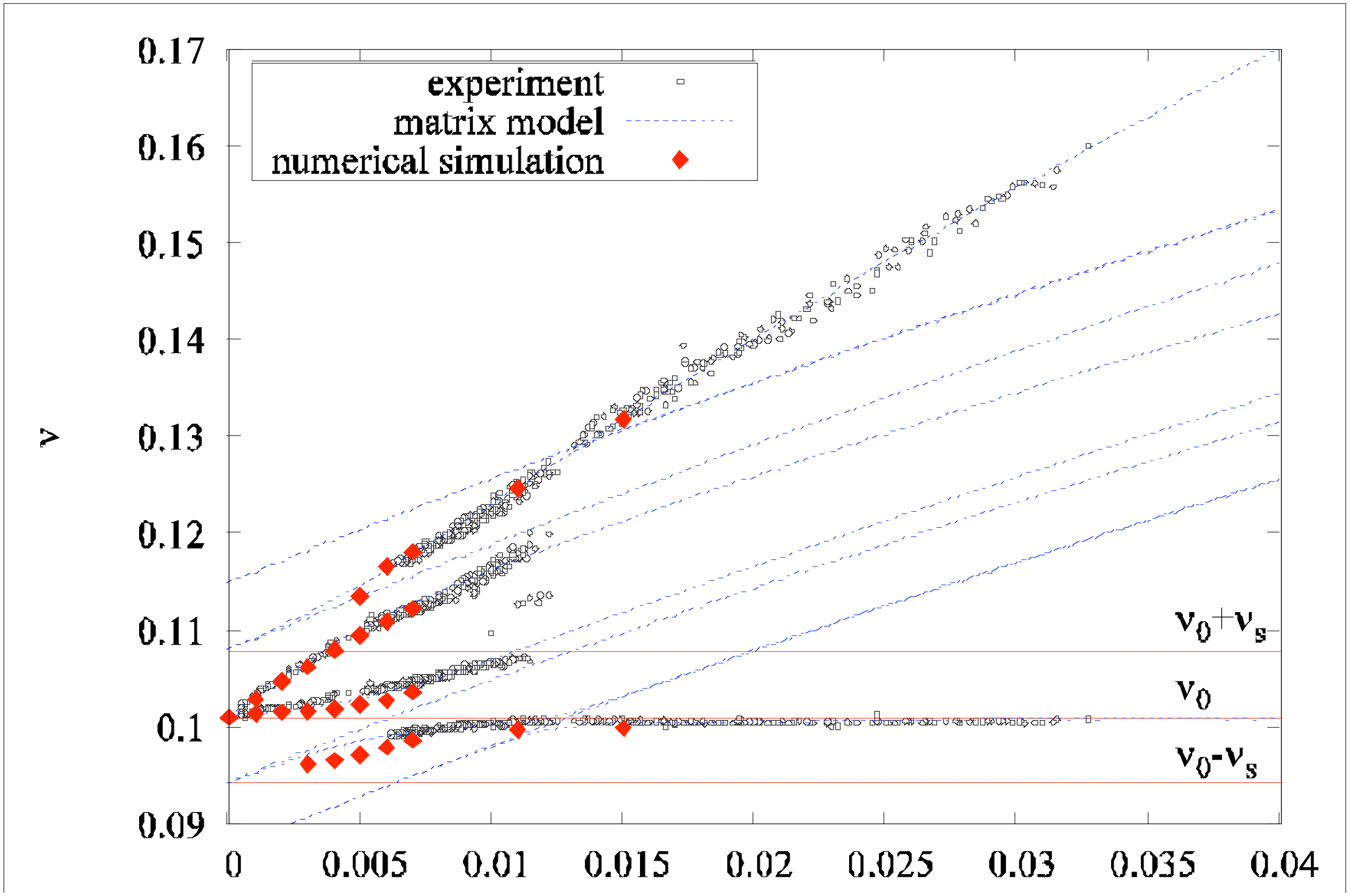
J. Qiang, LBNL

Averged H2+ Ion power density deposition on the cathode for 0, 100 MHz, 200 MHz cavities

Examples showing comparison of simulation & experiment

- VLEPP (BeamBeam3D)
- LEDA (IMPACT-Z)
- J-PARC (IMPACT-Z)
- SNS (IMPACT-Z)
- LCLS (IMPACT-Z)
- FNAL booster (Synergia)

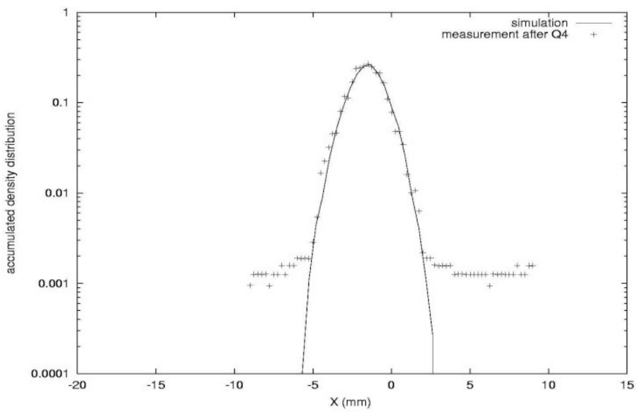
Synchrobetaron Mode Tunes vs. Beam-Beam Parameter: Measurement vs Simulation (BeamBeam3D)

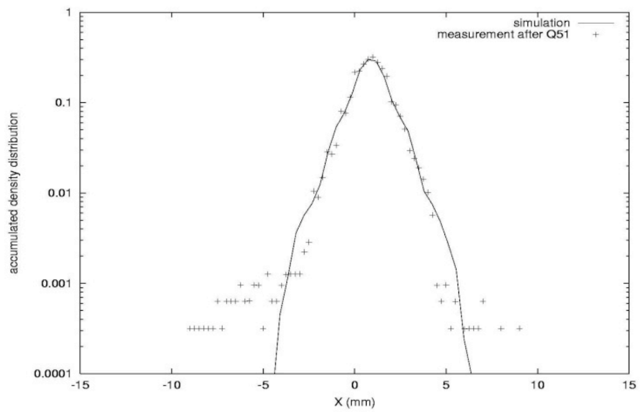


E. Stern and A. Valishev (FNAL)

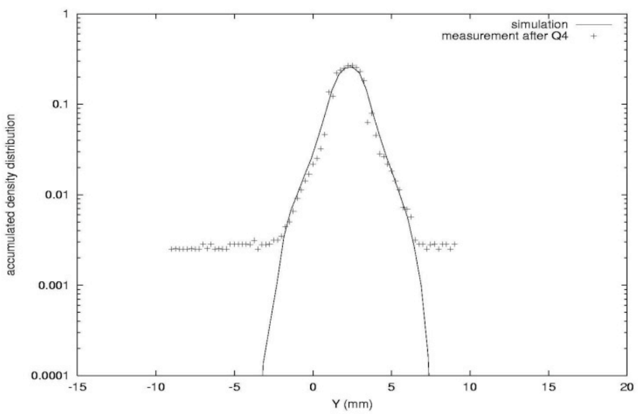
Experiment vs. Simulation for the Matched Beam (75 mA) LEBT/RFQ Initial Distribution

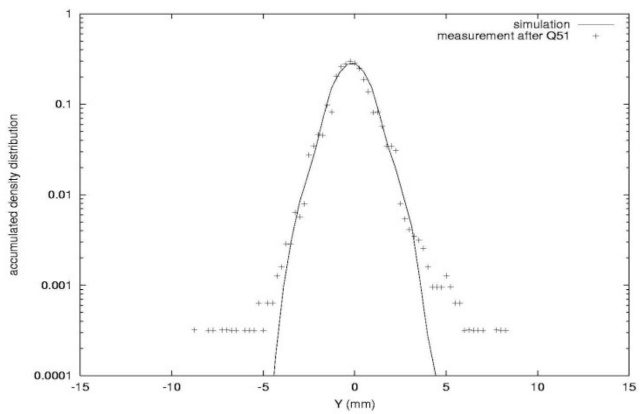
x





y





Simulated and measured profiles upstream

Simulated and measured profiles downstream

IMPACT is being used during the commissioning process of the J-PARC DTL

Simulation vs. measurements at J-PARC DTL:

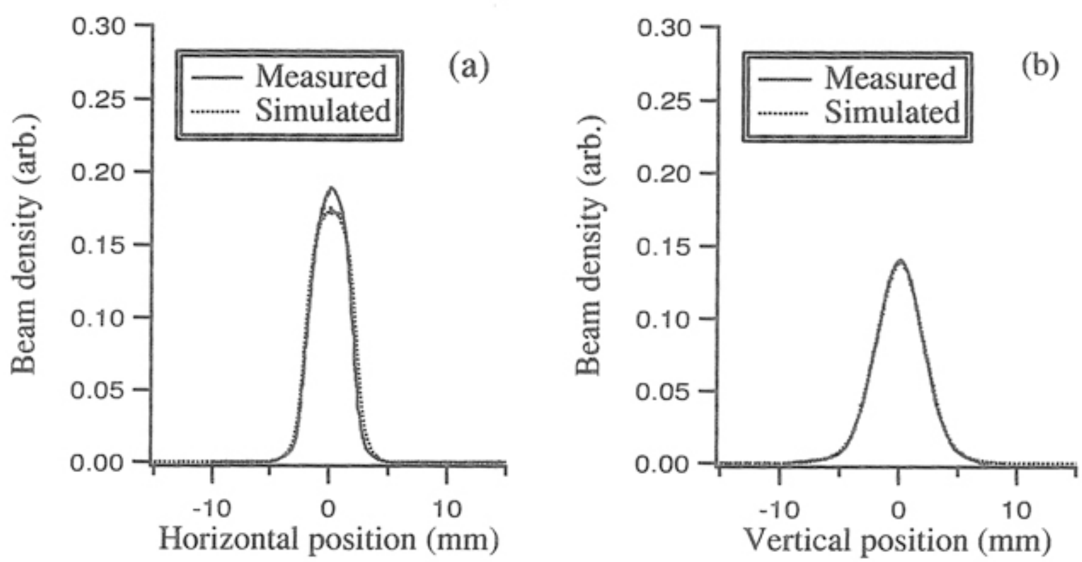


FIGURE 5. Beam profile measured with WS3 located before Q4. The quadrupole setting is the same with the emittance measurement, while the bunchers are turned off. (a) Horizontal beam profile. (b) Vertical beam profile. The beam profile obtained in an IMPACT simulation (Gaussian case) is also shown.

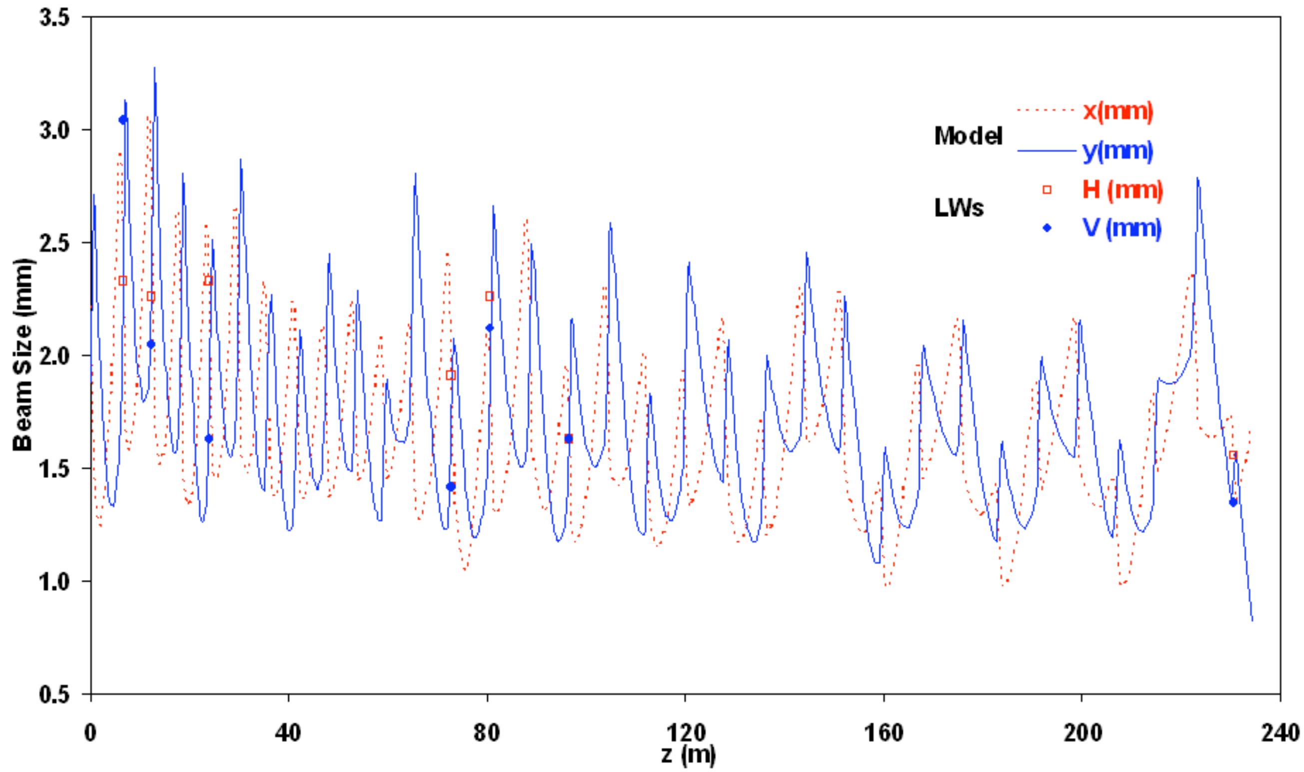
M. Ikegami, et. Al. "Comparison of particle simulation with J-PARC linac MEBT beam test results," proceedings of Beam Halo Dynamics, Diagnostics, and Collimation, Montauk, New York 2003.

IMPACT SIMULATION AND THE SNS LINAC BEAM *

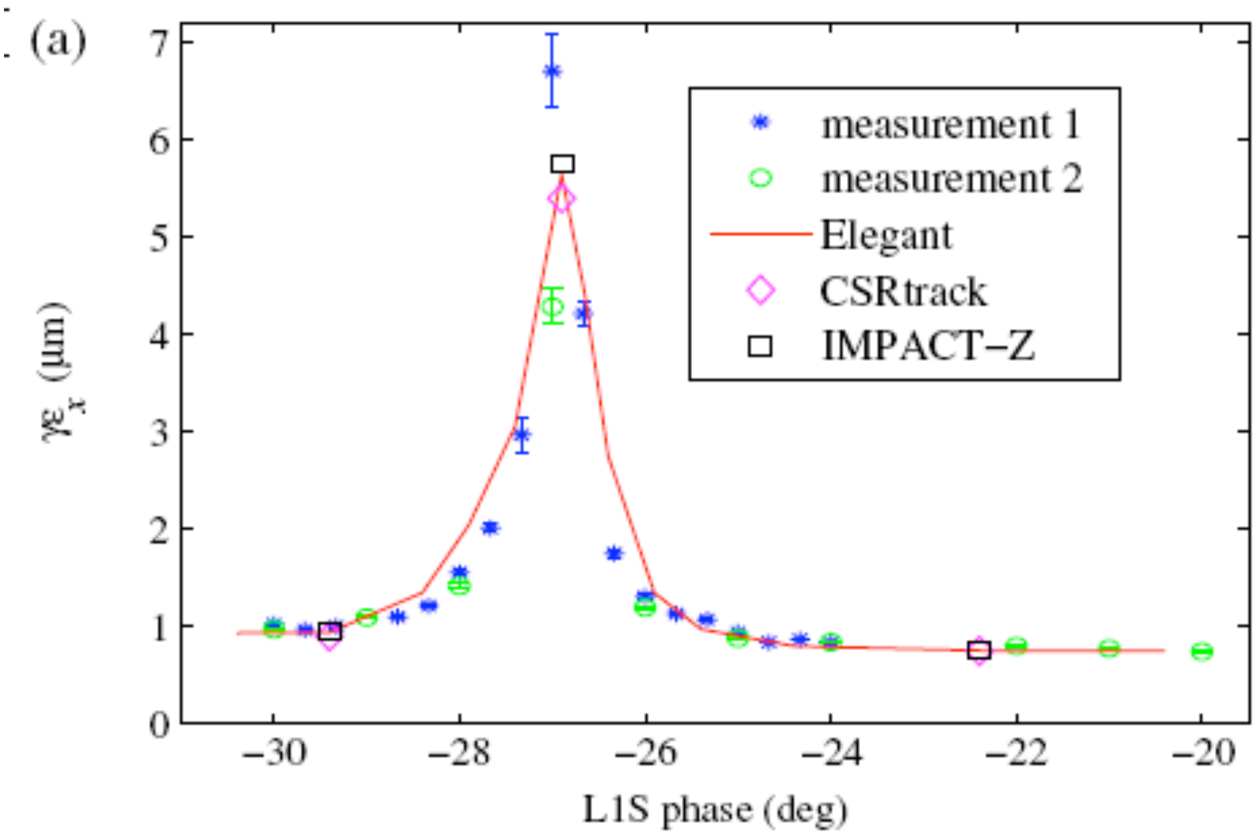
Y. Zhang[1], J. Qiang[2]
[1]Spallation Neutron Source, ORNL, Oak Ridge, TN 37831, USA
[2]Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

Abstract

Multi-particle tracking simulations for the SNS linac beam dynamics studies are performed with the IMPACT code. Beam measurement results are compared with the computer simulations, including beam longitudinal halo and beam losses in the superconducting linac, transverse beam Courant-Snyder parameters and the longitudinal beam emittance in the linac. In most cases, the simulations show good agreement with the measured results.



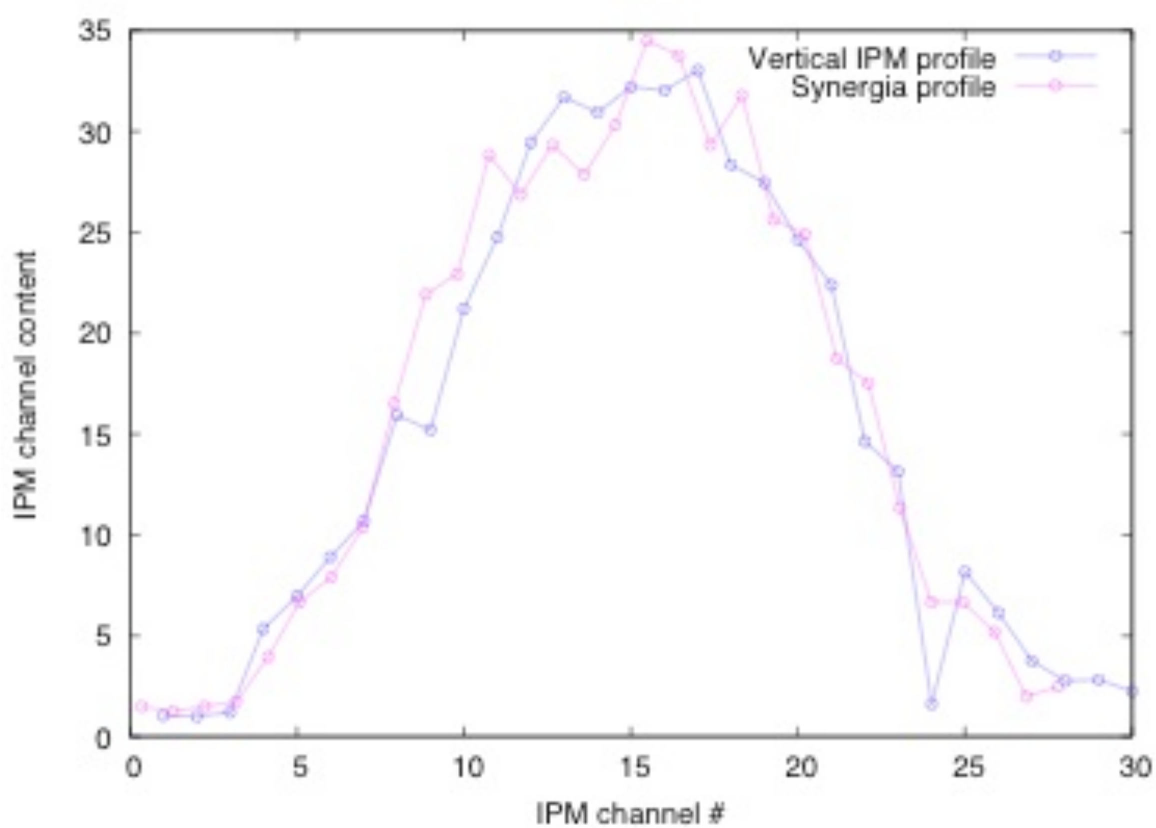
Comparison of IMPACT and other codes with measurements from LCLS



Horizontal emittance after BC1 at 250 pC.

From K. Bane, et. al. PRSTAB, 2009

FNAL booster: Comparison of experiment and simulation using Synergia*



Beam profile observed in the IPM (blue line) compared to a profile generated from the Synergia simulated beam, and smeared with the IPM response model.

* “Emittance dilution and halo creation during the first milliseconds after injection at the Fermilab Booster,” FERMILAB-CONF-05-407-CD

Future plans

- BeamBeam3d
  - Add electron lens model for beam-beam compensation
  - Add electron ring model for strong-strong study of eRHIC
  - Carry out strong-strong study of e-RHIC w/ electron lens compensation
  - Support JLab ELIC beam-beam studies
- IMPACT, ML/I
  - Enhance for PS2 space-charge studies
  - Carry out PS2 space charged studies
  - Add resistive wall impedance model
- General
  - Complete domain decomp/hybrid decomp study
  - Parallel scans
    - Complete implementation
    - Document and distribute throughout project
  - Documentation
    - Document code changes
    - Improve test case library
    - Improve user manuals
  - Optimization
    - Begin implementation of parallel optimization capabilities

Beam Dynamics-Related Publications (2007-present)

Refereed publications

1. J. Qiang, R. D. Ryne, M. Venturini, A. A. Zholents, High resolution simulation of beam dynamics in electron linacs for x-ray free electron lasers, submitted to Phys. Rev. ST Accel. Beams (2009).

2. K. Baptiste, J. Corlett, S. Kwiatkowski, S. Lidia, J. Qiang, F. Sannibale, K. Sonnad, J. Staples, S. Virostek, R. Wells, A CW normal-conductive RF gun for freee electron laser and energy recovery linac applications, Nuclear Instruments & Methods in Physics Research A 599, 9 (2009).

3. J. Qiang, J. M. Byrd, J. Feng, G. Huang, X-ray streak camera temporal resolution improvement using a longitudinal time-dependent field, Nuclear Instruments & Methods in Physics Research A 598, 465 (2009).

4. J.-L. Vay, Simulation of beams or plasmas crossing at relativistic velocity, Phys. Plasmas 15, 056701 (2008)

5. H. Shan, E. Strohmaier, and J. Qiang, Performance analysis of leading HPC architectures with BeamBeam3D, International Journal of High Performance Computing Applications, Vol. 22, Issue 1 (2008)

6. Z. Huang, Y. Ding, J. Qiang, Analysis of slice transverse emittance evolution in a photocathode RF gun, Nuclear Instruments & Methods in Pysics Research A 593, 148 (2008).

7. T. Ohkawa, M. Ikegami, J. Qiang, P. Saha, Macro-particle simulation study on transverse halo collimator for J-PARC linac, Nuclear Instruments & Methods in Pysics Research A 589, 1, (2008).

8. H. Shan, E. Strohmaier, and J. Qiang, Performance analysis of leading HPC architectures with BeamBeam3D, International Journal of High Performance Computing Applications, 22, 21, (2008)

9. G. Bell, D. Bruhwiler, A. Fedotov, A. Sobol, R. Busby, P. Stoltz, D. Abell, P. Messmer, I. Ben-Zvi, V. Litvinenko, Simulating the dynamical friction force on ions due to a briefly co-propagating electron beam, J. Comp. Phys., 227, 8714-8735 (2008), http://dx.doi.org/10.1016/j.jcp.2008.06.019 .

10. S. A. Veitzer and P. H. Stoltz, Simulations of electron generation and dynamics in a hollow cathode with applied magnetic field, Nuclear Instruments and Methods in Physics Research Section B, Volume 261, Issue 1-2, p. 204-208 (2007), http://dx.doi.org/10.1016/j.nimb.2007.04.291

Beam Dynamics-Related Publications (2007-present), cont.

Conference proceedings and technical notes

1. W. M. Fawley and J.-L. Vay, Use of the Lorentz-boosted frame transformation to simulate free-electron laser amplifier physics, Proc. Advanced Accelerator Conference (2008)
2. J. Qiang, Procedure for Automatic RIA Linac Error Studies Using the IMPACT Code, CBP Tech. Note 389, 2008.
3. D. Dechow, P. Stoltz, B. Norris, J. Amundson, Software components for electron cloud simulations, proceedings of EPAC08 conference.
4. R. Ryne, Advanced computing tools and models for accelerator physics, proceedings of EPAC08 conference.
5. J. Qiang, Wolfram Fischer, T. Sen, Strong-Strong Simulation of Long-Range Beam-Beam Effects at RHIC, proceedings of PAC07 conference, June 25-29, Albuquerque, 2007.
6. S. Bogacz, P. Chevtsov, Ya. Derbenev, P. Evtushenko, G. Krafft, A. Hutton, R. Li, L. Merminga, J. Musson, B. Yunn, Y. Zhang, J. Qiang, Advances on ELIC design studies, proceedings of the EPAC08 conference, June 23-27, Genoa, Italy, 2008.
7. V. Ranjbar, K. Paul, D.T. Abell, I. Ben-Zvi, J. Kewisch, R.D. Ryne, J. Qiang, High order modeling of an ERL for elecdtron cooing in the RHIC luminosity upgrade using MaryLie/IMPACT, proceedings of EPAC08 conference.
8. V. Ranjbar, K. Paul, D.T. Abell, I. Ben-Zvi, J. Kewisch, R.D. Ryne, J. Qiang, Impact of magnet misalignment in an ERL for electron cooling in RHIC, proceedings of EPAC08 conference.
9. W. Fischer, R. Calaga, N. Abreu, G. Robert-Demolaize, H.-J. Kim, T. Sen, J. Qiang, A. Kabel, U. Dorda, J.P.-Koutchouk, F. Zimmermann, Experiments with a DC wire in RHIC, Proc. PAC07.
10. T.P. Wangler et al, The RIAPMTQ/IMPACT beam dynamics simulation package, Proc PAC07 conference.
11. J. Amundson, P. Spentzouris, J. Qiang, R. Ryne, D. Dechow, SciDAC frameworks and solvers for multi-physics beam dynamics simulations, Proc. PAC07.
12. D. McCarron, J. Amundson, W. Pellico, P. Spentzouris, R. Tomlin, L. Spentzouris, Measurement and simulation of space-charge dependent tune separation in FNAL Booster, Proc. PAC07.
13. E. Stern, J. Amundson, P. Sentzouris, A. Valishev, J. Qiang, R. Ryne, Development of 3D beam-beam simulation for the Tevatron, Proc. PAC07.
14. Y. Ding, Z. Huang, C. Limborg-Deprey, J. Qiang, LCLS beam dynamics studies with the 3-D parallel IMPACT-T code, Proc. PAC07.
15. J. Qiang, I. V. Pogorelov, R. Ryne, Parallel Beam Dynamics Simulation Tools for Future Light Source Linac Modeling, Proc. PAC07.
16. J. Qiang, J. Byrd, J. Feng, G. Huang, Streak Camera Temporal Resolution Improvement Using a Time-Dependent Field, Proc. PAC07.
17. J. Qiang et al., Numerical Study of Coulomb Scattering Effects on Electron Beam from a Nano-Tip, Proc. PAC07.
18. J. Qiang, I.V. Pogorelov, R.D. Ryne, Parallel beam dynamics simulation tools for future light source linac modeling, Proc. PAC07.
19. I V. Pogorelov, J. Qiang, R. Ryne, M. Venturini, A. Zholents R. Warnock, Simulation of the Microbunching Instability in Beam Delivery Systems for Free Electron Lasers, Proc. PAC07.
20. D. Abell, P.J.Mullowney, K. Paul, V.H. Ranjbar, J. Qiang, R.D. Ryne, 3D Integrated Green functions for the Poisson equation, Proc. PAC07.

Frameworks, infrastructure, and additional applications

See next talk

EXTRA SLIDES

Additional information on IMPACT and BeamBeam3D algorithms (J. Qiang)
Tools for boosted frame calculations (J.-L. Vay)
ELIC beam-beam studies (Y. Zhang)

1D CSR Wake Field Including Transient Effects

$$\frac{dE(s,\phi)}{cdt} = -\frac{2e^2}{4\pi\epsilon_0 3^{1/3} R^{2/3}}\left(\int_{s-s_L}^{s} \frac{1}{(s-s')^{1/3}}\frac{\partial\lambda(s')}{\partial s'}ds' + \frac{\lambda(s-s_L)-\lambda(s-4s_L)}{s_L^{1/3}}\right)$$

$$W(s) = \begin{cases} -\frac{4}{R}\frac{1}{(\phi_m+2x)}\lambda(s-\frac{R}{6}\phi_m^2(\phi_m+3x)) & \textit{for source in front of the bend} \\ \frac{4}{R}\left(\frac{\lambda(s-\Delta s_{max}}{(\phi_m+2x)} + \int_{s-\Delta s_{max}}^{s}\frac{1}{\psi+2x}\frac{\partial\lambda}{\partial s'}ds'\right) & \textit{for source inside the bend} \end{cases}$$

$$s - s' = \frac{R\psi^3}{24}\frac{\psi+4x}{\psi+x}$$

Ref: 1) E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov,
Nucl. Instrum. Methods Phys. Res., Sect. A398, 373 (1997).
2) M. Borland, Phys. Rev. Sepecial Topics - Accel. Beams 4, 070701 (2001).
3) G. Stupakov and P. Emma, ``CSR Wake for a Short Magnet in Ultrarelativistic Limit,''
SLAC-PUB-9242, 2002.

Thin Lens Approximation for Crab Cavity Deflection

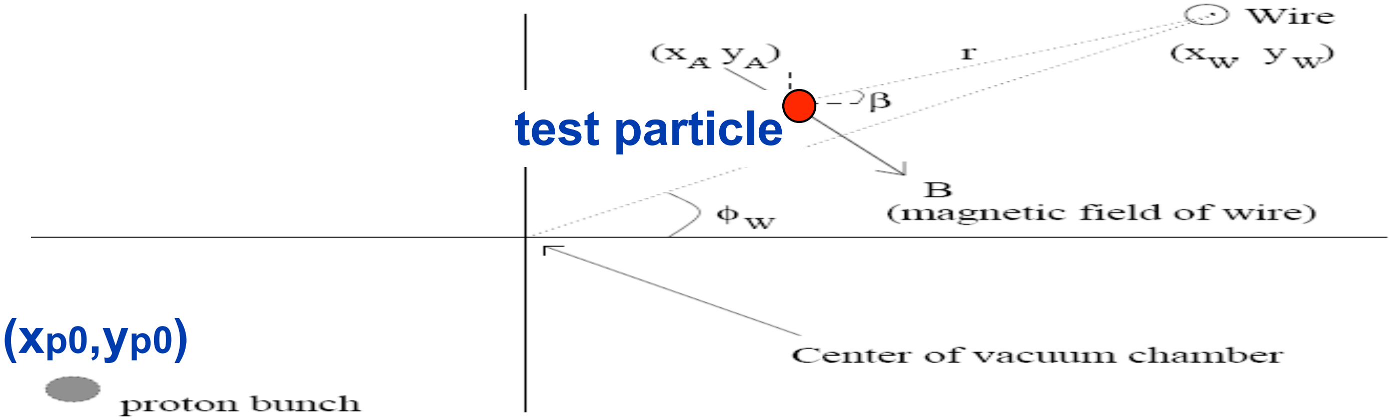
$$x^{n+1} = x^n$$

$$Px^{n+1} = Px^n + \frac{qV}{E_s}\sin(\omega z^n / c)$$

$$z^{n+1} = z^n$$

$$\delta E^{n+1} = \delta E^n + \frac{qV}{E_s}\cos(\omega z^n / c)x^n$$

Model of Conducting Wire Compensation



$$\Delta x'_{BB} = \frac{2N_p r_p}{\gamma_p}\frac{x_A - x_{P0}}{[(x_A - x_{P0})^2 + (y_A - y_{P0})^2]}\left\{1 - \exp[-\frac{1}{2\sigma^2}[x_A - (x_{P0})^2 + (y_A - y_{P0})^2]]\right\}$$

$$\Delta y'_{BB} = \frac{2N_p r_p}{\gamma_p}\frac{y_A - y_{P0}}{[(x_A - x_{P0})^2 + (y_A - y_{P0})^2]}\left\{1 - \exp[-\frac{1}{2\sigma^2}[(x_A - x_{P0})^2 + (y_A - y_{P0})^2]]\right\}$$

$$\Delta x'_W = -\frac{B_y L}{(B\rho)} = \frac{\mu_0}{2\pi}\frac{I_W L}{(B\rho)}\frac{x_W - x_A}{(x_W - x_A)^2 + (y_W - y_A)^2}$$

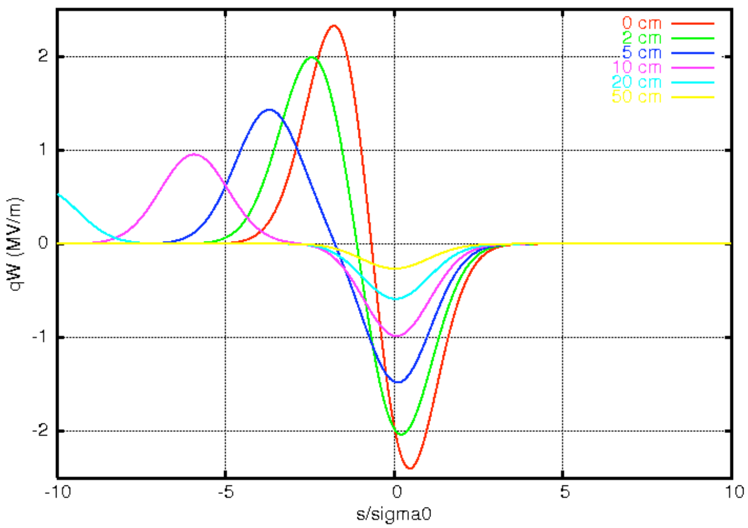
$$\Delta y'_W = \frac{B_x L}{(B\rho)} = \frac{\mu_0}{2\pi}\frac{I_W L}{(B\rho)}\frac{y_W - y_A}{(x_W - x_A)^2 + (y_W - y_A)^2}$$

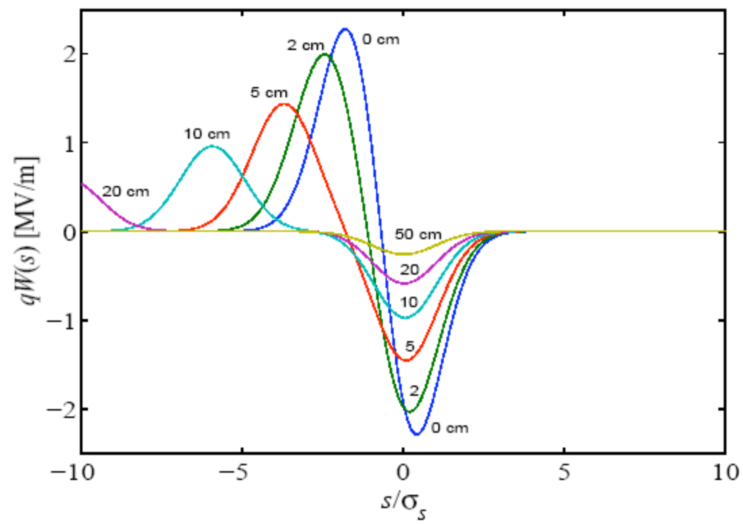
$$x_W = x_{P0}, \quad y_W = y_{P0},$$

$$\frac{\mu_0}{2\pi}\frac{I_W L}{(B\rho)} = \frac{2N_p r_p}{\gamma_p} \Rightarrow I_W L = ecN_p$$

B.Erdelyi and T.Sen, “Compensation of beam-beam effects in the Tevatron with wires,” (FNAL-TM-2268, 2004).

Test of the CSR Wake Implementation for a Short Bend and Benchmark with LCLS

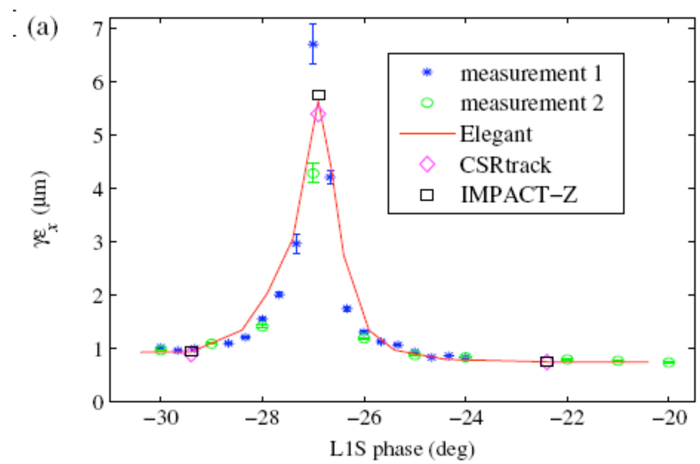




R = 1.5 m, Arc=10 cm

From G. Stupakov and P. Emma

From K. Bane, et. al. PRSTAB, 2009



Horizontal emittance after BC1 at 250 pC.

Up Sampling of Initial Particle Distribution

—Maintain global properties of the original distribution

- emittances
- current profile,
- energy-position correlation

—Reduce shot noise of the original particle distribution by using more macroparticles

—A 6D box centered at the original is used to generate new macroparticles

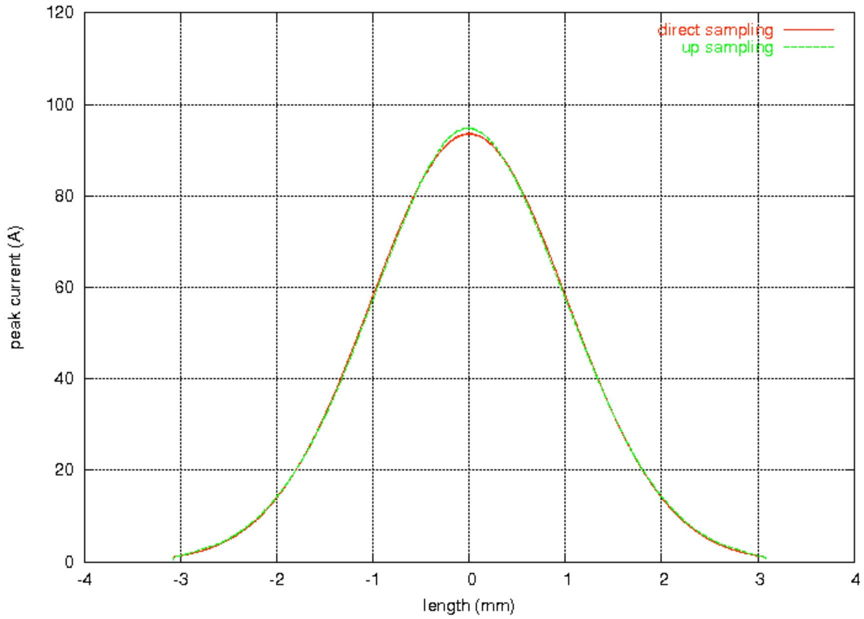
—Uniform sampling in transverse 4D

—Linear sampling in longitudinal position following original current profile

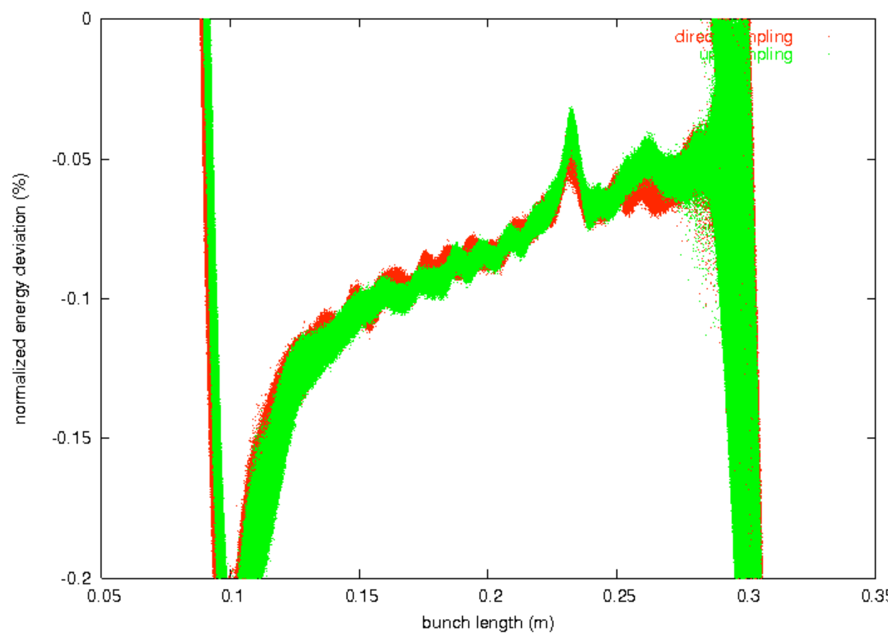
—Cubic spline to obtain the energy-position correlation

A Comparison of Direct Sampling and Up Sampling

Initial current profile from direct sampling and up sampling



Final longitudinal phase space from direct sampling and up sampling



Developing the tools for "boosted frame" calculations.

J.-L. Vay*[1,4]

in collaboration with

W.M. Fawley[1], A. Friedman[2,4], M.A. Furman[1] ,
C.G. Geddes*[1], D.P. Grote[2,4], S. Markidis[1,3,4]

[1]Lawrence Berkeley National Laboratory, CA
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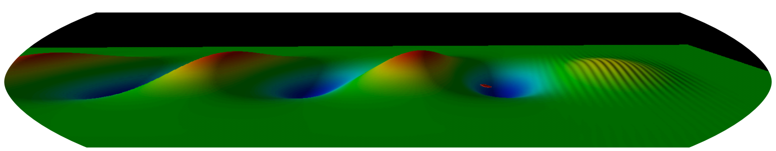
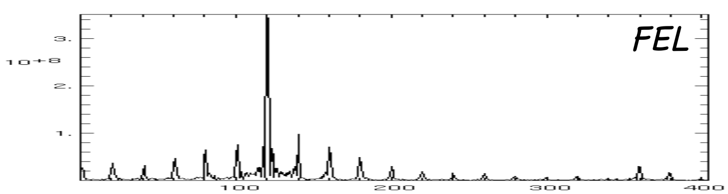
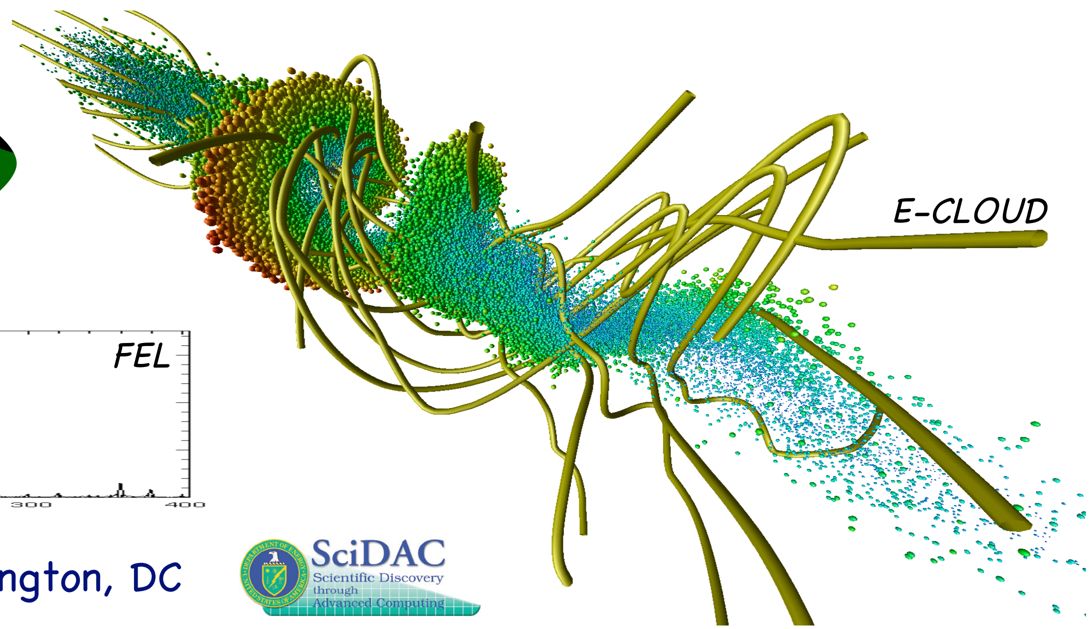
[3]University of Illinois, Urbana-Champaign, IL
[4]Heavy Ion Fusion Science Virtual National Laboratory

*Scidac funded
Leverage from institution,
LARP, LDRD and SBIR funding.







SCIDAC Review, April 21-22, 2009, Washington, DC

Concept

- # of computational steps grows with the full range of space and time scales involved

- key observation
  - ***range*** of space and time scales is ***not*** a Lorentz invariant*

    scales as γ^2 in x and t

  - the optimum frame to minimize the range is not *necessarily* the lab frame

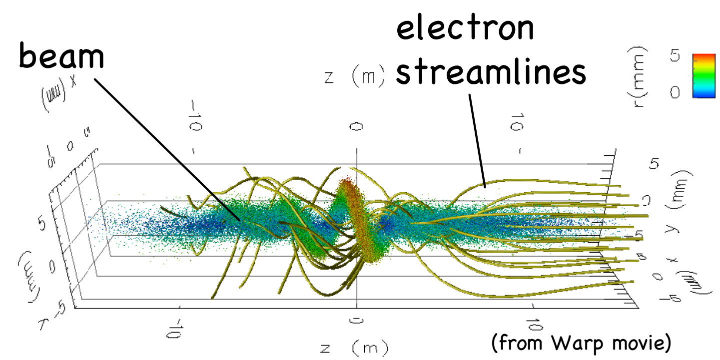
Choosing optimum frame of reference to minimize range can lead to dramatic speed-up for relativistic matter-matter or light-matter interactions.

*J.-L. Vay, *Phys. Rev. Lett.* **98**, 130405 (2007)

Calculation of e-cloud induced TMC instability of a proton bunch

- Proton energy: γ=500 in Lab
- L= 5 km, continuous focusing

Code: Warp (Particle-In-Cell)



CPU time (2 quad-core procs):
- **lab frame: >2 weeks**
- **frame with γ^2=512: <30 min**

Speedup x1000

Seems simple but ⚠. Algorithms which work in one frame may break in another. Example: the Boris particle pusher.

- Boris pusher ubiquitous
  - In first attempt of e-cloud calculation using the Boris pusher, the beam was lost in a few betatron periods!
  - Position push: $\mathbf{X}^{n+1/2} = \mathbf{X}^{n-1/2} + \mathbf{V}^n \Delta t$ -- no issue
  - Velocity push: $\gamma^{n+1}\mathbf{V}^{n+1} = \gamma^n\mathbf{V}^n + \frac{q\,\Delta t}{m}\left(\mathbf{E}^{n+1/2} + \frac{\gamma^{n+1}\mathbf{V}^{n+1} + \gamma^n\mathbf{V}^n}{2\,\gamma^{n+1/2}} \times \mathbf{B}^{n+1/2}\right)$

    issue: $\mathbf{E}+\mathrm{v}\times\mathbf{B}=0$ implies $\mathbf{E}=\mathbf{B}=0$ => large errors when $\mathbf{E}+\mathrm{v}\times\mathbf{B}\approx 0$ (e.g. relativistic beams).

- Solution
  - Velocity push: $\gamma^{n+1}\mathbf{V}^{n+1} = \gamma^n\mathbf{V}^n + \frac{q\,\Delta t}{m}\left(\mathbf{E}^{n+1/2} + \frac{\mathbf{V}^{n+1} + \mathbf{V}^n}{2} \times \mathbf{B}^{n+1/2}\right)$
- Not used before because of implicitness. We solved it analytically*

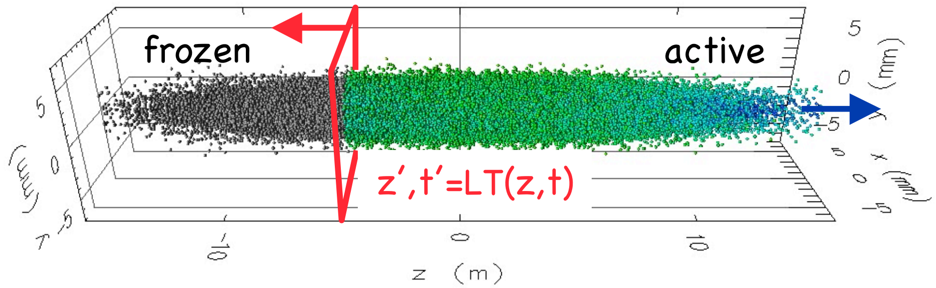
$$\begin{cases} \gamma^{i+1} = \sqrt{\dfrac{\sigma + \sqrt{\sigma^2 + 4(\tau^2 + u^{*2})}}{2}} \\ \mathbf{u}^{i+1} = [\mathbf{u}' + (\mathbf{u}' \cdot \mathbf{t})\mathbf{t} + \mathbf{u}' \times \mathbf{t}]/(1+t^2) \end{cases}$$

(with $\mathbf{u} = \gamma\mathbf{v}$, $\mathbf{u}' = \mathbf{u}^i + \frac{q\Delta t}{m}\left(\mathbf{E}^{i+1/2} + \frac{\mathbf{v}^i}{2} \times \mathbf{B}^{i+1/2}\right)$, $\boldsymbol{\tau} = (q\Delta t/2m)\mathbf{B}^{i+1/2}$; $u^* = \mathbf{u}' \cdot \boldsymbol{\tau}/c$, $\sigma = \gamma'^2 - \tau^2$, $\gamma' = \sqrt{1 + u'^2/c^2}$, $\mathbf{t} = \boldsymbol{\tau}/\gamma^{i+1}$).

*J.-L. Vay, *Phys. Plasmas* **15**, 056701 (2008)

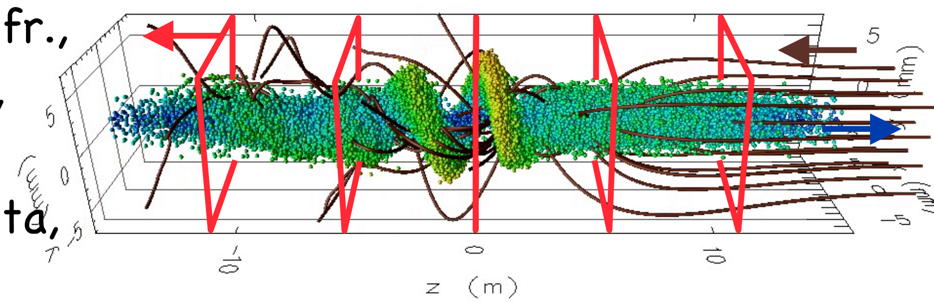
Other complication: input/output

- Often, initial conditions known and output desired in laboratory frame
  - relativity of simultaneity => inject/collect at plane(s) ⊥ to direction of boost.
- Injection through a moving plane in boosted frame (fix in lab frame)
  - fields include frozen particles,
  - same for laser in EM calculations.



- Diagnostics: collect data at a collection of planes
  - fixed in lab fr., moving in boosted fr.,
  - interpolation in space and/or time,
  - already done routinely with Warp

  for comparison with experimental data, often known at given stations in lab.



Other accomplishements; future work

- Accelerator lattice in Warp: added linear maps, boosted frame tracking
  - will apply to e-cloud simulations for SPS, LHC, ILC, etc.
- W. Fawley (LDRD LBNL) applying Warp to numerical study of Free Electron Lasers (FEL) and Coherent Synchrotron Radiation (CSR)
  - detailed benchmarking of FEL physics: spontaneous emission, coherent spontaneous emission, amplifier gain, sideband emission effects of subharmonic bunching, etc.,
  - simulation of CSR: examine transverse size effects normally neglected by theory and computationally prohibitively expensive under normal lab frame E&M calculations.
- Pursue development and detailed algorithmic/physics studies of boosted frame calc. for problems of interest to HEP: LWFA, E-cloud, FEL, CSR, …
- Apply Warp's novel EM solver with mesh refinement (MR) in lab frame and boosted frame simulations
  - LWFA stage in 3-D: required resolution may vary by more than 2 orders of magnitude in transverse directions. Applying MR:
    - up-to 10^4 saving on # grid cells for 10 GeV,
    - up-to 10^8 saving on # grid cells for 1 TeV.

ELIC Beam-Beam Simulation Studies

Yuhong Zhang, JLab

Ji Qiang, LBNL

Introduction: Model, Code & ELIC Parameters

Simulation Model

- **Single or multiple IP, head-on collisions**
- **Ideal rings for electrons & protons**
  - → **Using a linear one-turn map**
  - → **Does not include nonlinear optics**
- **Include radiation damping & quantum excitations in the electron ring**

Numerical Convergence Tests

to reach reliable simulation results, we need

- **Longitudinal slices >= 20**
- **Transverse mesh >= 64 x 128**
- **Macro-particles >= 200,000**

Simulation Scope and Limitations

- **10k ~ 30k turns for a typical simulation run (multi-days of NERSC supercomputer)**
- **0.15 s of storing time (12 damping times)**
  - → **reveals short-time dynamics with accuracy**
  - → **can't predict long term (>min) dynamics**

BeamBeam3D Code

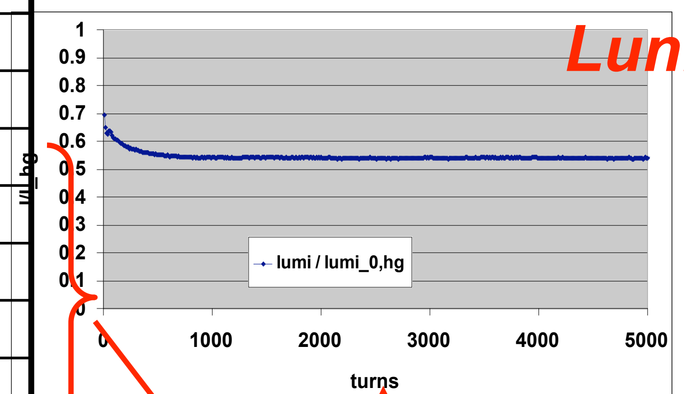
•Developed at LBL by Ji Qiang
•Based on particle-in-cell method
•A ***strong-strong self-consistent*** code
•Includes longitudinal dim. (multi-slices)

		Proton	Electron
Energy	GeV	150	7
Current	A	1	2.5
Particles	10^{10}	1.04	0.42
Hori. Emit., norm.	µm	1.06	90
Vert. Emit., norm.	µm	0.042	3.6
β_x / β_y	mm	5 / 5	5 / 5
σ_x / σ_y	µm	5.7/1.1	5.7/1.1
Bunch length	mm	5	5
Damping time	turn	---	800
Beam-beam parameter		0.002 0.01	0.017 0.086
Betatron tune ν_x and ν_y		0.71 0.70	0.91 0.88
Synchrotron tune		0.06	0.25
Peak luminosity	$cm^{-2}s^{-1}$	7.87×10^{34}	

Simulation Results: Nominal Parameters

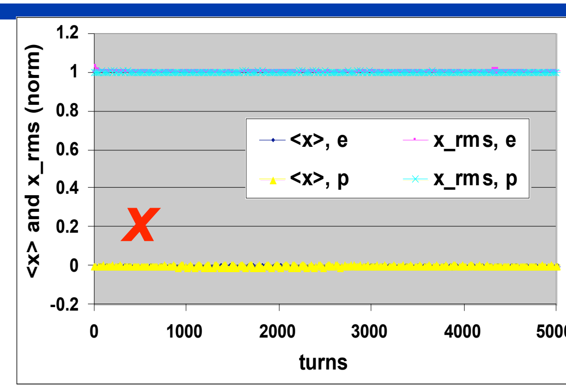
- Simulations started with two Gaussian bunches with design parameters, reached equilibrium after one damping time
- No coherent beam-beam instability observed.
- Luminosity stabled at $\boldsymbol{4.3 \cdot 10^{34}\ cm^{-2}s^{-1}}$ after damping time
- Sizes & lengths for both bunches remain design values except
- Vertical size & emittance of electron bunch increased by a factor of 1.8 and 2.7 respectively

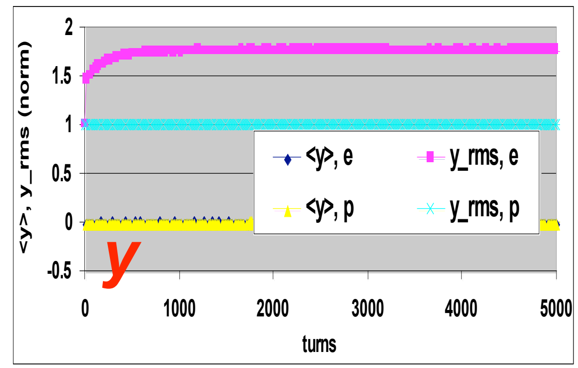
	Electron	proton
Luminosity	$4.3 \cdot 10^{34}\ cm^{-2}s^{-1}$	
x_rms (norm)	1.00	1.00
x_emit (norm)	0.97	1.00
y_rms (norm)	1.76	1.00
y_emit (norm)	2.73	1.01
z_rms (norm)	1	1
z_emit (norm)	1	1
h. tune shift	0.017	0.002
v. tune shift	0.087	0.010

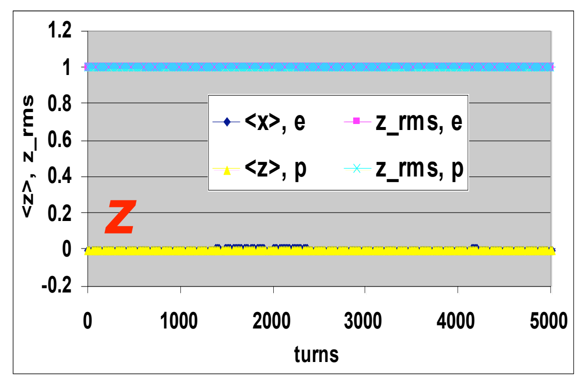


Luni

Normalized to design parameters

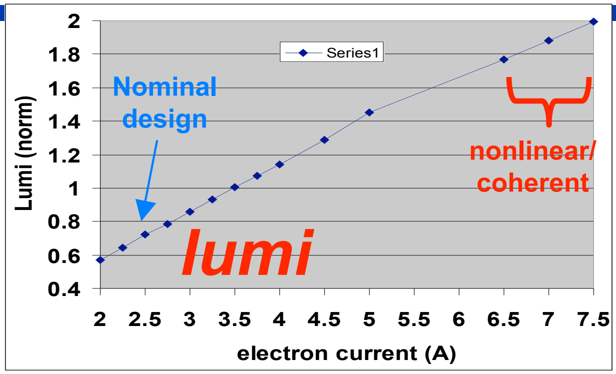


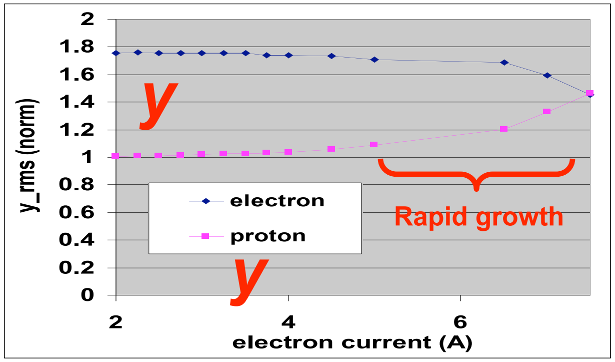


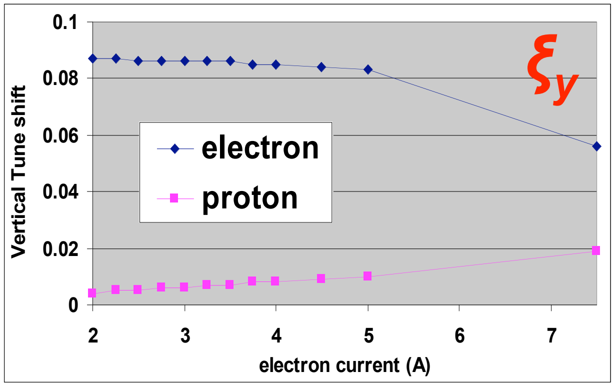


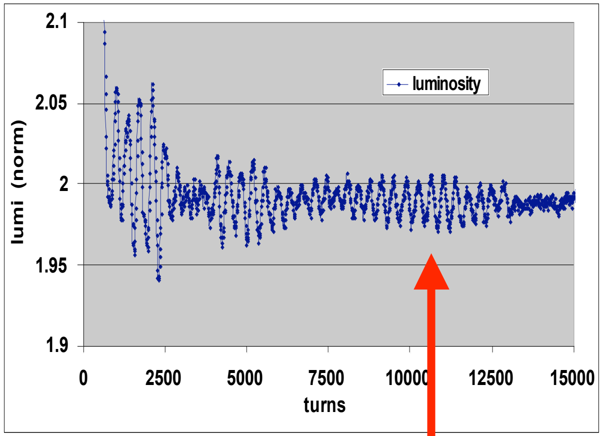
Electron Current Dependence of Luminosity

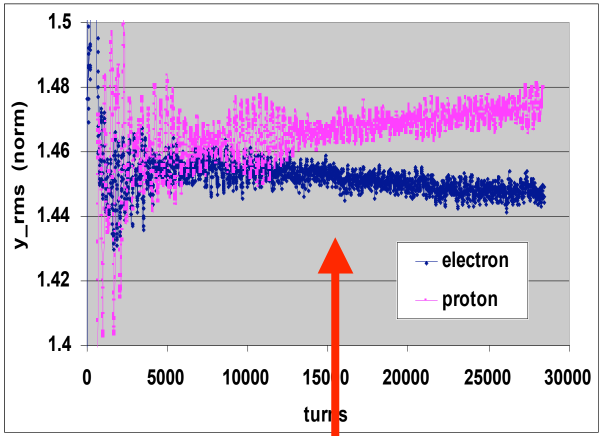
- Luminosity increase as electron current almost linearly (up to 6.5 A) while bunch repetition rate remains the same,
- Proton bunch vertical emittance blowup when electron current is at above 7 A
- Coherent beam-beam instability (vertical size) observed at 7 ~ 7.5 A.







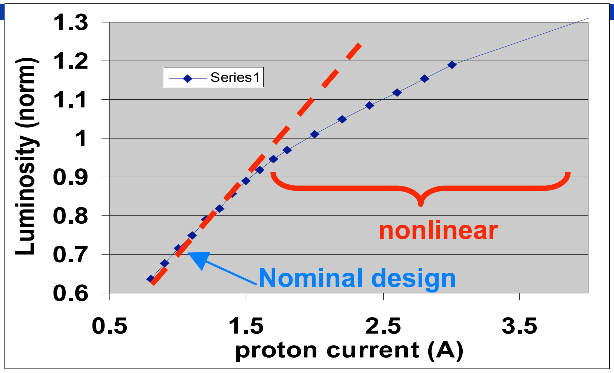


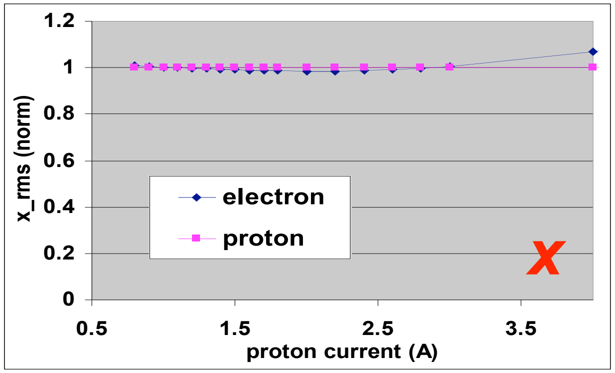


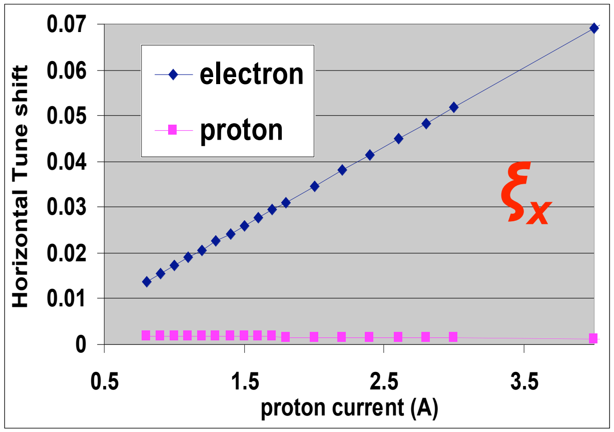
Coherent beam-beam instability

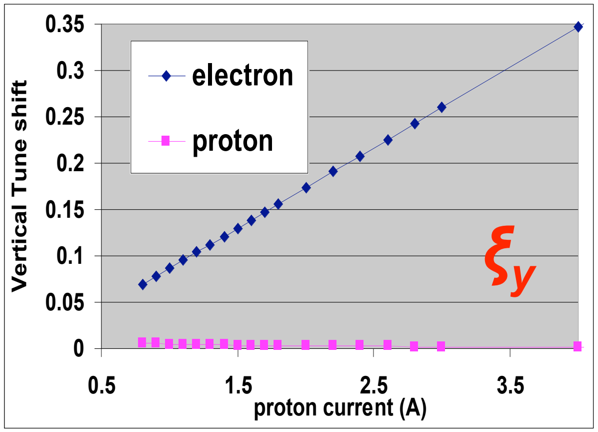
Proton Current Dependence of Luminosity

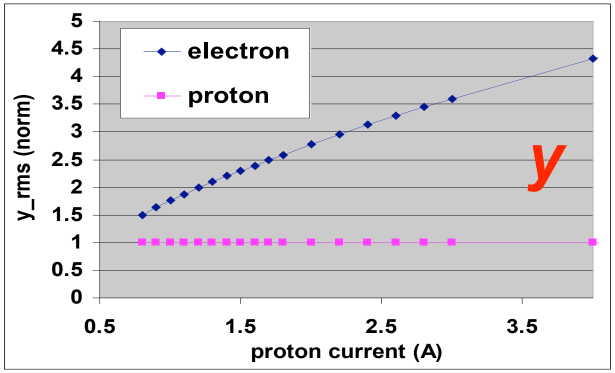
- Increasing proton beam current by increasing proton bunch charge while bunch repetition rate remain same, hence also increasing beam-beam interaction
- Luminosity increase as proton beam current first approximately linearly (up to 1.5 A), then slow down as nonlinear beam-beam effect becomes important
- Electron beam vertical size/emittance increase rapidly
- Electron vertical and horizontal beam-beam tune shift increase as proton beam current linearly



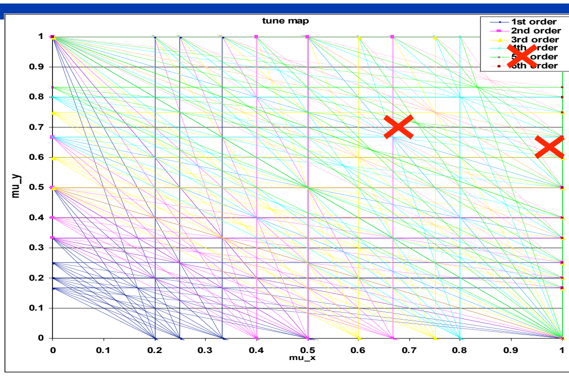


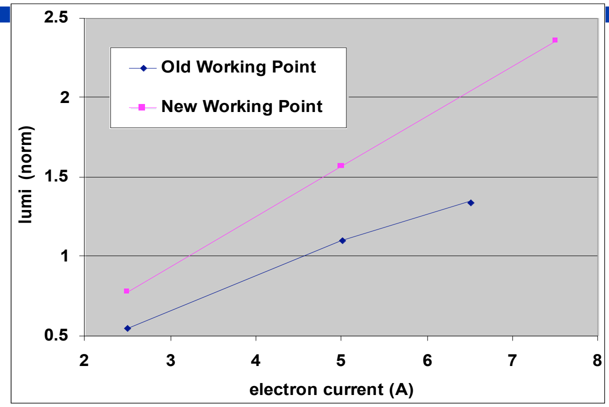


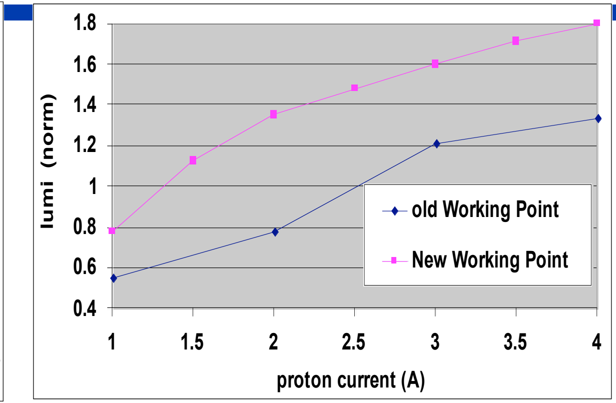




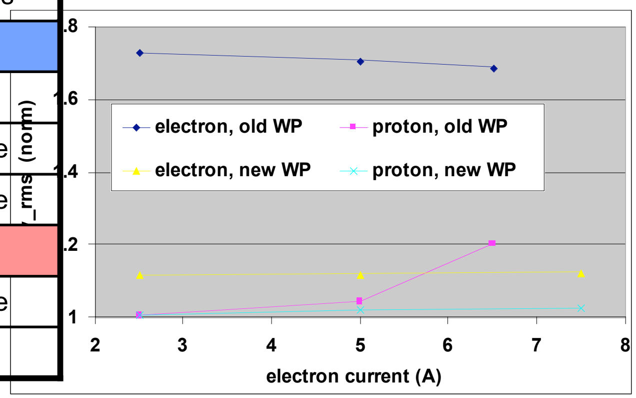
Searching for New Working Point

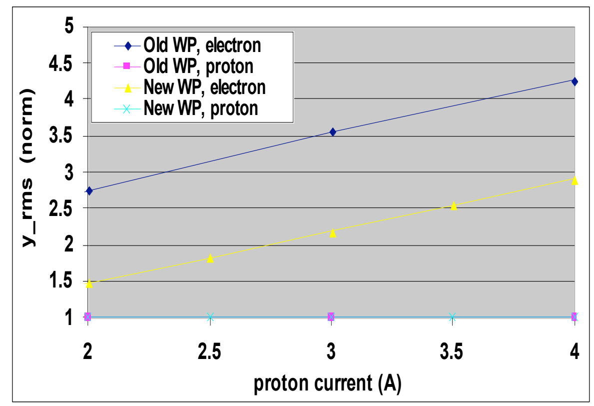






Electron ν_x, ν_y	Proton ν_x, ν_y	Luminosity 10^{34} cm^{-2} s^{-1}
0.91, 0.88	0.71, 0.7	4.15
0.71, 0.7	0.91, 0.88	3.22
0.73, 0.725	0.91, 0.9	Unstable
0.748, 0.75	0.91, 0.88	Unstable
0.63, 0.645	0.71, 0.7	5.77
0.91, 0.88	0.63, 0.645	Unstable
0.96, 0.46	0.71, 0.7	2.38



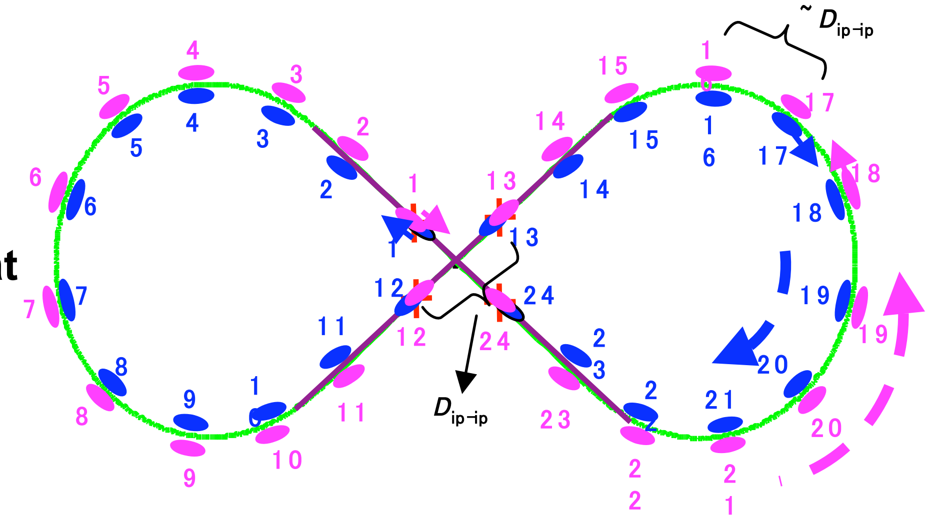


- Equilibrium luminosity strongly depends on synchrotron & betatron tune working point, which should be away from synchrotron-betatron resonance lines
- Tune footprint, enlarged by beam-beam effect, should avoid cross low order resonance lines

Simulation studies show

- systematic better luminosity over beam current regions with new working point,
- coherent instability is excited at same electron beam current, ~ 7 A

Systems of Multiple IPs & Multiple Bunches

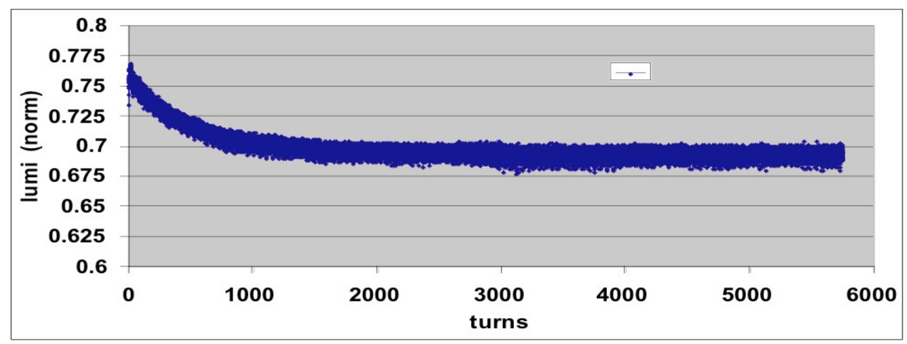


ELIC full capacity operation

- **4 interaction Points, 1.5 GHz collision frequency, over 10500 bunches stored for each beams**
- **Bunches are coupled together by collisions at 4 IPs & through other beam physics phenomena**

Simplified model

- **12 bunches for each beam, collisions at all 4 IPs**
- **A bunch takes 24 steps for one complete turn in Figure-8 rings**
- **Total 48 collisions per turn for two 12-bunch sets**



Simulation results

- **Simulated system stabilized after one damping time (more than 100k collisions)**
- **Luminosity per IP reaches 5.48x10^{34} m^{-1}s^{-2}, a 5% additional loss over hour-glass effect due to multi-bunch coupling**

Future Plan

- Continuation of code validation and benchmarking
- Single IP and head-on collision
  - — Coherent beam-beam instability
  - — Synchrot-betatron resonance and working point
  - — Including non-linear optics and corrections
- Multiple IPs and multiple bunches
  - — Coherent beam-beam instability
- Collisions with crossing angle and crab cavity
- Beam-beam with other collective effects

- Part of SciDAC COMPASS project
- Working with LBL and TechX and other partners for developing and studying beam dynamics and electron cooling for ELIC conceptual design